João André Viseu Simões Lima

A METHODOLOGICAL FRAMEWORK TO SUPPORT ENERGY DECISION-MAKERS IN INVESTMENT PLANNING FOR ENERGY EFFICIENCY PROGRAMS IN THE RESIDENTIAL SECTOR

Dissertation within the Integrated Master’s Degree in Electrical and Computer Engineering, Specialization in Energy and presented to the Department of Electrical and Computer Engineering of the Faculty of Sciences and Technology of the University of Coimbra

February 2020

FACULTY OF SCIENCES AND TECHNOLOGY
DEPARTAMENT OF ELECTRIC AND COMPUTER ENGENEERING

A methodological framework to support energy decision-makers in investment planning for energy efficiency programs in the residential sector

Dissertation within the Integrated Master's Degree in Electrical and Computer Engineering, Specialization in Energy and presented to the Department of Electrical and Computer Engineering of the Faculty of Sciences and Technology of the University of Coimbra

Author
João André Viseu Simões Lima

Supervisors
Professor Doctor Álvaro Filipe Peixoto Cardoso de Oliveira Gomes
Professor Doctor Carla Margarida Saraiva de Oliveira Henriques

Jury

President	**Professor Doctor Humberto Manuel Matos Jorge** **Assistant Professor in the Department of Electrical and Computers Engineering**
Vowel	**Professor Doctor Dulce Helena Carvalho Coelho** **Adjunct Professor in the Coimbra Institute of Engineering**
Supervisor	**Professor Doctor Álvaro Filipe Peixoto Cardoso de Oliveira Gomes** **Assistant Professor in the Department of Electrical and Computers Engineering**

---

1 2 9 0
UNIVERSIDADE Ð
COIMBRA

Coimbra, February, 2020

"Resilience is very different than being numb. Resilience means you experience, you feel, you fail, you hurt. You fall. But, you keep going." – **Yasmin Mogahead**

Acknowledgments

Apesar desta dissertação estar escrita em inglês, gostaria de reservar esta parte à minha língua materna, de modo a poder expressar da melhor forma os meus agradecimentos a todos os que tornaram este meu percurso possível.

O meu primeiro agradecimento dirige-se aos meus orientadores nesta tese, ao professor doutor Álvaro Gomes e à professora doutora Carla Henriques, por me terem inicialmente introduzido ao tema e por toda a disponibilidade para fornecerem material, orientações e toda a ajuda necessária à conclusão deste trabalho.

Ao Núcleo de Estudantes de Engenharia Eletrotécnica e de Computadores, porque para além de todas as competências extracurriculares que me proporcionou, e todos os desafios que me fez trabalhar para superar, deu-me o privilégio de criar e desenvolver inúmeras amizades que ainda hoje se mantêm.

Quero também dirigir um obrigado a todos aqueles que, durante o meu percurso universitário, se revelaram mais do que simples colegas de curso. À minha Squad, que durante tantos anos nesta luta, foram sempre a base de todos os dias no departamento, e tornavam mais fácil sair de casa naqueles dias em que a vontade era menos. Ao gang do LGE, porque se houve alturas em que duvidei que ia conseguir entregar esta tese, a maioria foi causada por eles, mas é também muito graças a eles que este trabalho hoje está feito.

Também tenho que dirigir o meu agradecimento a todos os meus restantes amigos mais próximos, uns mais recentes e outros que me acompanharam em grande parte do meu percurso escolar e académico, e em especial a pessoas como a Carina, a Ana, o Tiago, a Maria Inês, a Luísa, o Fábio e a Inês, o meu obrigado por, há mais ou menos tempo, terem estado sempre deste lado a contribuir para a manutenção da minha sanidade mental durante todas as etapas que já ultrapassei, e conto agora com vocês para continuarem a desempenhar essa função nas que estão para vir.

Ao Rancho Folclórico e Etnográfico de Eira Pedrinha e a todos os seus elementos, porque mais do que uma distração para aqueles momentos em que a cabeça já precisa de descanso, são uma família, e todos os dias senti também o apoio de todos.

Um dos meus maiores agradecimentos vai para a minha namorada, Mariana, por ter sido uma das principais responsáveis por tudo de mais positivo que eu consegui nos últimos tempos, e tanto esta, como todas as minhas futuras conquistas e desafios só farão sentido se ela estiver sempre do meu lado. Por todo o apoio, ajuda e carinho que sempre me deste, só consigo agradecer devolvendo tudo o que fazes por mim de igual ou melhor forma.

Por último, mas de todo em último, a toda a minha família, mas especial a algumas pessoas em particular. Em primeiro, aos meus avós, por serem provavelmente as pessoas com mais vontade de me verem chegar até aqui. Avós, vocês estão a ver o vosso neto formado! À minha irmã, por ter sido o maior presente que a vida me podia dar, e por trazer alegria e energia a todos os dias. E por fim, àqueles que estão lá todos os dias desde sempre e que vivem e "aturam" em primeira mão todos os meus melhores e piores momentos, e a quem devo tudo o que tenho e sou hoje, os meus pais. Nunca vou ter palavras suficientes para vos agradecer toda a ajuda, apoio e confiança de que, apesar de tudo, eu ia conseguir chegar aqui, mas pelo menos em especial para o meu pai posso dizer o que sei que ele vai gostar de ler neste momento: afinal aquele "camelo" tinha razão!

Este trabalho teve apoio da Fundação para a Ciência e Tecnologia (FCT) e do Fundo Europeu de Desenvolvimento Regional (FEDER) via COMPETE – Programa Operacional Competitividade e Internacionalização (POCI), no âmbito dos projetos T4ENERTEC (POCI-01- 0145-FEDER-029820) e UID/MULTI/00308/2020.

This work has been supported by the European Regional Development Fund through the COMPETE 2020 Program and FCT, under projects UID/MULTI/00308/2020, and "T4ENERTEC" POCI-01-0145-FEDER-029820.

Abstract

Energy efficiency is seen as an essential tool to reduce energy consumption contributing to a more sustainable society. Thus, promoting the efficient allocation of resources to the deployment of energy efficiency measures is important.

In this context, the assessment of which energy efficiency measures should be selected for public funding is usually done according to their energy savings, avoided emissions and cost-effectiveness. Furthermore, energy savings and avoided emissions are generally computed considering the use phase of the technologies / measures without accounting for the manufacturing, construction, installation, recycling or final disposal phases. However, as efficiency increases, the importance of the energy consumption during these stages also increases. Usually, cost-effectiveness assessment is based on the total resource cost (to evaluate if money savings from the energy efficiency program exceeds the total program costs). On the other hand, multiple objectives are usually at stake when energy efficiency actions are assessed, and different stakeholders may have different and conflicting objectives, making the decision process more demanding. Therefore, an alternative approach is proposed in this work by means of the development of a multi-objective model to appraise and evaluate portfolios of energy efficiency measures. Three objectives are considered in this model: minimizing the savings to investment ratio, maximizing the minimum difference between the energy savings and the energy embodied in the energy efficiency measures and minimizing the energy payback time of the portfolio. The energy savings and the avoided emissions are computed considering a life-cycle perspective. The usefulness of the proposed model is subsequently validated by considering data from the Portuguese building stock. Finally, the results obtained with these models and with the results reached with a more traditional approach (i.e. based on energy and monetary savings obtained during the operation phase) are then contrasted.

Keywords: Energy Efficiency, Residential Sector, Lifecycle Assessment, Multiobjective Analysis, Portfolio Model.

Resumo

A eficiência energética é vista como um instrumento essencial para reduzir o consumo de energia, contribuindo para uma sociedade mais sustentável. Assim, é fundamental promover a alocação eficiente de recursos através da implementação de medidas de eficiência energética.

Neste contexto, a seleção e avaliação das medidas de eficiência energética que serão alvo de financiamento público são geralmente feitas com base na poupança energética, emissões evitadas e análise custo-benefício. Estes indicadores são geralmente calculados tendo em conta a fase de operação das tecnologias/medidas sem contemplar as fases de fabrico, construção, instalação, reciclagem ou deposição final. No entanto, à medida que a eficiência destas medidas aumenta, a importância do consumo de energia nas diferentes fases do ciclo de vida destas também aumenta. Normalmente, a análise custo-benefício baseia-se no custo total da medida (de modo a avaliar se a poupança, em valor monetário, associada à adoção do programa de eficiência energética excede os respetivos custos totais). Por outro lado, as medidas de eficiência energética são avaliadas tendo em consideração objetivos múltiplos, por vezes contraditórios, e diferentes partes interessadas, tornando o processo de tomada de decisão mais exigente. Por conseguinte, neste trabalho propõe-se uma abordagem alternativa através do desenvolvimento de um modelo multiobjectivo para avaliar portfólios de medidas de eficiência energética. Neste modelo são contemplados três objetivos: a minimização do rácio poupança investimento, a maximização da mínima diferença entre a poupança energética e a energia incorporada nas medidas de eficiência energética e a minimização do tempo de retorno energético do portfólio. A poupança de energia e as emissões evitadas são calculadas tendo em conta uma perspetiva de ciclo de vida. A utilidade do modelo proposto é posteriormente validada através da utilização de dados respeitantes ao parque residencial português. Finalmente, os resultados obtidos com este modelo são contrastados com os resultados alcançados com uma abordagem mais tradicional (isto é, com base na poupança energética e monetária calculadas tendo em conta apenas a fase de operação).

Palavras-chave: Eficiência energética, Setor Residencial, Análise ciclo de vida, Análise Multi-objetivo, Modelo de portfólio.

Índice

List of Figures ... xii

List of Tables ... xiv
  Acronyms ... xvi

1. Introduction ... 1
  1.1. Motivation ... 1
  1.2. Aim of the Work ... 4
  1.3. Structure ... 4

2. Portuguese Building Stock ... 6
  2.1. Characterization ... 6
  2.2. Energy Consumption in the Residential Sector ... 10
  2.3. Residential Building Characterization ... 12
    2.3.1. Single-dwelling Building ... 12
    2.3.2. Multi-dwelling Building ... 15

3. The Genetic Algorithm (GA) ... 17
  3.1. The NSGA-II (Non-dominating Sorting Genetic Algorithm) ... 18
    3.1.1. Initial Population ... 18
    3.1.2. Fitness Evaluation ... 18
    3.1.3. Tournament Selection ... 19
    3.1.4. Simulated Binary Crossover ... 19
    3.1.5. Polynomial Mutation ... 20
    3.1.6. Stopping Criteria ... 21

4. Energy Efficiency Measures ... 22
  4.1. Selected Measures ... 22
    4.1.1. Constructive Measures ... 22
    4.1.2. Technological Measures ... 24
  4.2. Energy Efficiency Measures Lifecycle Characterization ... 27
  4.3. Energy Efficiency Measures Performance ... 28
    4.3.1. SIR ... 28
    4.3.2. PBT ... 28
    4.3.3. EPBT (Local and Global) ... 29
    4.3.4. CPBT ... 29

5. Methodology ... 31
  5.1. Selection of the objective functions ... 31
  5.2. Mathematical Model ... 32
  5.3. Genetic Algorithm Parameterization ... 34

6. Results And discussion ... 37
  6.1. LCA approach vs Traditional approach ... 40
  6.2. Portfolio impact on different strategies ... 42

7. Conclusion ... 45
  7.1. Future Work ... 46

References ... 48

ANNEXES 52

LIST OF FIGURES

Figure 2.1 - Portuguese buildings by typology [11] 6
Figure 2.2 - Portuguese buildings by year of construction [12] 7
Figure 2.3 - Portuguese buildings that require refurbishment [11] 8
Figure 2.4 - Portuguese buildings per type of refurbishment needed [11] 8
Figure 2.5 - Portuguese buildings' efficiency class adapted from [16] 10
Figure 2.6 - Portuguese buildings' efficiency class after rehabilitation [16] 10
Figure 2.7 - Portuguese residential sector energy consumption by type of fuel [17] 11
Figure 2.8 - Portuguese residential sector energy consumption by end-use [13] 12
Figure 2.9 - Single-dwelling building (until 1960) [18] 13
Figure 2.10 - Single-dwelling building (from 1961 to 1990) [18] 14
Figure 2.11 - Single-dwelling building (from 1991 to 2012) [18] 14
Figure 2.12 - Single-dwelling building (from 2013) [18] 14
Figure 2.13 - Multi-dwelling building (until 1960) [18] 15
Figure 2.14 - Multi-dwelling building (from 1991 to 2013) [18] 16
Figure 3.1 - Schematic representation of the GA functioning 18
Figure 3.2 - Tournament selection [21] 19
Figure 3.3 - Single binary crossover [22] 20
Figure 6.1 - Number of implementations of each measure (1 to 50) in each portfolio using an LCA approach. 37
Figure 6.2 - Final NSGA-II population 38
Figure 6.3 - Number of implementations of each measure (1 to 50) for the non-dominated solutions 38
Figure 6.4 - Number of implementations of each measure (1 to 50) in each portfolio using a traditional approach. 41
Figure 6.5 - Portfolio return vs Risk 42
Figure 6.6 - Portfolio EPBT vs Risk 43

LIST OF TABLES

Table 2.1 - Portuguese building's glazed façades by type of glaze in 2011 [13] 9
Table 2.2 - Operative comfort temperature [18] 12
Table 2.3 - Typical Portuguese single-dwelling residence characteristics by era [18] 13
Table 2.4 - Typical Portuguese multi-dwelling residence characteristics by era [18] 15
Table 4.2 - Portuguese energy mix and emission factor 27
Table 5.1 - Indicators' correlation table.. 31

Acronyms

ADENE –Agency for Energy

BAT – Best Available Technology

BAU – Business-as-usual

CEE – Buildings' Energy Code

CFL – Compact Fluorescent Lamp

CPBT – Carbon Payback Time

CO2eq – Carbon Dioxide Equivalent

EEF – Energy Efficiency Fund

EPBT – Energy Payback Time

EPDB – Energy Performance of Buildings Directive

EPS – Expanded Polystyrene Foam

ERSE - Energy Services Regulatory Authority

EU – European Union

FPC – Portuguese Carbon Fund

GA – Genetic Algorithm

GHG – Greenhouse Gases

GWP – Global Warming Potential

LCA – Lifecycle Assessment

LED – Light Emitting Diode

MS – Member States

Mt - Megaton

NECP – National Energy and Climate Plans

NEEAP – National Energy Efficiency Action Plan

NSGA-II – Non-dominated Sorting Genetic Algorithm

PBT – Payback Time

PPEC – Efficient Electric Energy Consumption Promotion Plan

PVC – Polyvinyl Chloride

RECS – Commerce and Services Buildings Energy Performance Regulation

REH – Energy Performance Regulation of Housing Buildings

SBX – Single-binary Crossover

SCE – Portuguese National System for Energy and Indoor Air Quality Certification of Buildings

SIR – Savings to Investment Ratio

XPS – Extruded Polystyrene Foam

1. INTRODUCTION

1.1. Motivation

Improving efficiency in the way we use and consume energy is one of the possible ways of fighting climate change and resource depletion. In the year of 2017, Portugal recorded a total of 47.9 Mt CO2eq emissions, of which 29.5% were originated from energy generation and transformation [1]. One of the largest contributors to the impact of energy consumption is the residential sector. Data from PORDATA referring to the year of 2017 [2] show that this sector is responsible for 26.3% of energy consumption in Portugal. Additionally, 25.3% of the certified residential buildings by the CEE (Buildings' Energy Code) are classified as D and only 10.4% are classified as A or above. This system classifies buildings with a rate from F to A+, according to reference values for energy consumed by year for space heating, space cooling and water heating [15]. Therefore, there is a big potential for energy efficiency improvements in this sector, which can have significant positive impacts on the reduction of the country's Greenhouse Gas (GHG) emissions in the future. In fact, both European and national entities have been making efforts in order to foster changes in energy use behaviours and the adoption of more efficient technologies in households. These efforts and incentives are present in the legislative framework (i.e. directives and legislation) that is responsible for endorsing policies and programs to promote energy efficiency.

In the European Union (EU), several policies have been implemented in order to reduce the energy consumption associated to the building stock of its Member States (MS). The Directive nº 2002/91/CE established several regulations addressing European buildings, in terms of their energy performance [3]. This Directive, known as the Energy Performance of Buildings Directive (EPBD), required the implementation of a buildings' energetic certification, and was amended by Directive 2010/31/UE, with the aim of improving the energy efficiency of buildings both in terms of energy consumption and energy sources [4]. This Directive also states that inspection strategies should be implemented to assess the energy performance of heating and cooling systems, to determine minimum energy performance requirements for new buildings or buildings that will suffer major refurbishments.

The high energy efficiency improvement potential of the residential sector is clearly acknowledged in Directive 2012/27/UE. This Directive states that improving the refurbishment rate of residential buildings is critical to achieve the EU's GHG emission objectives. It establishes that all the EU MS must refurbish at least 3% of the government buildings per year and outlines long-term strategies for the building stock refurbishment to be included in the National Energy Efficiency Action Plans (NEEAPs) of each country. These plans had the purpose of determining the energy consumption of each individual country, plan energy efficiency measures, long-term renovation strategies and improvements in order to achieve the EU 2020 target of 20% improvement in energy efficiency, enacted in 2012. Each country is now set to elaborate a 10-year integrated national and climate plan (NECP), outlining the strategies to meet the 2030 energy efficiency targets where the target was increased from 20% to 27% [5]. Directives 2010/31/UE and 2012/27UE suffered some changes through Directive (UE) 2018/844, in order to accelerate the renovation of residential buildings and achieve a decarbonized housing stock by 2050.

Looking into the Portuguese panorama in terms of energy efficiency legislation, the first regulation related to efficiency in refurbished buildings was present in Decree-Laws nº 79/2006 and nº80/2008, which established that buildings subject to major refurbishments should have the same energy efficiency requirements as new buildings. Currently, the Portuguese legislation regarding the energy performance of the existing building stock subject to major interventions and new residential buildings is compiled in Directive nº 2010/31/EU, which encompasses the REH (Energy Performance Regulation of Housing Buildings), the SCE (Portuguese National System for Energy and Indoor Air Quality Certification of Buildings) and the RECS (Commerce and Services Buildings Energy Performance Regulation).

Following the EU legislation for energy efficiency, the Directive nº 2012/27/UE was transposed into the Portuguese legal order by Decree-Law nº 68-A/2015, to define actions to achieve the 2011 Energy Efficiency Plan and the EU 2050 carbon goals. Most of the guidelines from the European Parliament and Council Directive were already present in Portuguese legislation, concerning the NEEAP for the period between 2013 to 2016, approved by the Resolution nº20/2013, with the goal of reducing primary energy until 2020. Following the EU guidelines, the NEEAP was enlarged to cover six specific areas: transports, residential and services, industry, state, behaviours and agriculture. Within this scope, several programs were created, including measures to improve energy efficiency. The implementation of NEEAP 2016 is accomplished through regulatory measures, fiscal differentiation mechanisms and financial funds to help implement energy efficiency measures [6]. Some of these funds are:

- EEF (Energy Efficiency Fund), created by Decree-Law nº 50/2010, aimed at supporting PNAEE measures.
- PPEC (Efficient Electric Energy Consumption Promotion Plan), promoted by ERSE (Energy Services Regulatory Body).
- FPC (Portuguese Carbon Fund), created by Decree-Law nº 71/2006, to promote projects that aim to reduce GHG emissions.
- Portugal 2020 and other communitarian financial instruments.

Evaluating and selecting the energy efficiency measures that should be elected for funding by energy efficiency programs is a complex process, because it requires the consideration of multiple features. These can be related to the refurbishment of buildings or to the installation of more efficient technologies, requiring distinct aspects for their evaluation (economic, energetic and environmental) or having to consider different types of building.

Portfolio optimization theory has been studied and adjusted to help decision makers select energy efficiency projects and measures to be funded. In this context [7], considered the volatility of the performance effect of each project in order to select the portfolio of energy efficiency measures to be funded. Trachanas et al. [8] used a minimax regret approach to select the best portfolios of energy efficiency measures. Forouli et al. [9] proposed a risk-oriented optimization model to optimize budget allocation to energy efficiency projects, where the evaluation was based on energy savings and risk implementation, subject to technical and financial constraints. More recently, [10] combined portfolio theory with Economic Input-Output Lifecycle Assessment to suggest two model formulations to support the design of energy efficiency programs in India. Two objectives were considered in this study: maximizing the Savings to Investment Ratio (SIR), as a measure of investment return and maximizing the minimum deviation of GHG avoided emissions (energy saved) over the portfolio lifetime from the embodied GHG emitted (energy use) in the manufacturing of the technologies.

The progress and evolution of energy technologies towards the reduction of energy consumption in their use phase gives a prominent role to the energy and GHG embodied during the manufacturing and disposal of these technologies. Nevertheless, from the literature review conducted, it is possible to conclude that the portfolio models generally used in the selection of energy efficiency measures rarely consider the lifecycle impact of the measures evaluated. Therefore, the development of alternative modelling approaches following a lifecycle perspective is timely and relevant.

1.2. Aim of the Work

The present dissertation is aimed at building a methodological framework that supports decision makers in the selection of the portfolios of efficiency measures to be funded. This modelling framework is based on a multi-objective optimization approach, considering the energy and environmental lifecycle performance of the energy efficiency measures under scrutiny. The portfolios are then obtained following heuristic methods, specifically the Non-dominated Sorting Genetic Algorithm II (NSGA-II), with a constrained multi-objective approach. Additionally, a selection and characterization of the set of measures to be considered as a starting point for the model's instantiation is also envisaged and required.

1.3. Structure

This dissertation is organized in 7 main chapters. In Chapter 1 a brief description of the European and national legislation framework regarding energy efficiency is provided, followed by the main challenges that decision-makers face in the selection of the portfolios of energy efficiency measures that should be targeted for funding. In addition, a brief literature review of the portfolio models typically used in this context is also provided and the motivation and research aims of this work are also given. Chapter 2 gives a global overview of the Portuguese building stock, as well as the energy consumption in this sector. In this chapter, a detailed description of the main characteristics of the typical buildings in Portugal is presented. Chapter 3 presents the method chosen to select the portfolios of energy efficiency measures, specifically the genetic algorithm NSGA-II. Chapter 4 details the selected energy efficiency measures that will be considered as a starting point, in terms of their energetic characteristics such as embodied energy and energy savings, as well as their performance according to several commonly used indicators to analyse their efficiency. Chapter 5 presents the methods used to form the portfolios, specifying the selected indicators to be considered as objectives in the mathematic model, as well as the parameterization of the Genetic Algorithm to obtain the optimal solutions. Chapter 6 shows the main results and their discussion. Chapter 7 presents the main conclusions of this work, and some suggestions for future work.

2. PORTUGUESE BUILDING STOCK

2.1. Characterization

In order to best evaluate the necessities and energy efficiency potential of the Portuguese building stock, it is important to look into its characteristics in terms of construction and energy consumption. In this chapter, it is possible to find a global overview of the building sector in Portugal, as well as the characteristics that are most relevant to this work, namely the number of buildings by type, the number of buildings per year of construction, the number of buildings with refurbishment necessities, construction materials, energy consumption by energy source and by end-use. Finally, the building characteristics used in the calculation of this study will be detailed.

The most recent data reveals that, in 2018, there were 3,604,407 buildings with 5,954,548 households, which represents a growth of 0.2% comparing to 2017 [11]. It is possible to see a clear slowdown in the construction of residential buildings, considering that between 2001 and 2011 there was a growth of 11.6% and between 2011 and 2018 that value decreased to 1.4%. These values represent a ratio of 1.7 households per building.[11]. The ratio of habitants per household has also decreased to 1.7.

In terms of the type of residential building, slight changes have been observed, from 2013 to 2018, mainly with the increase of T1 and T0 households. The constitution of the Portuguese housing stock according to 2018 data can be observed in Figure 2.1.

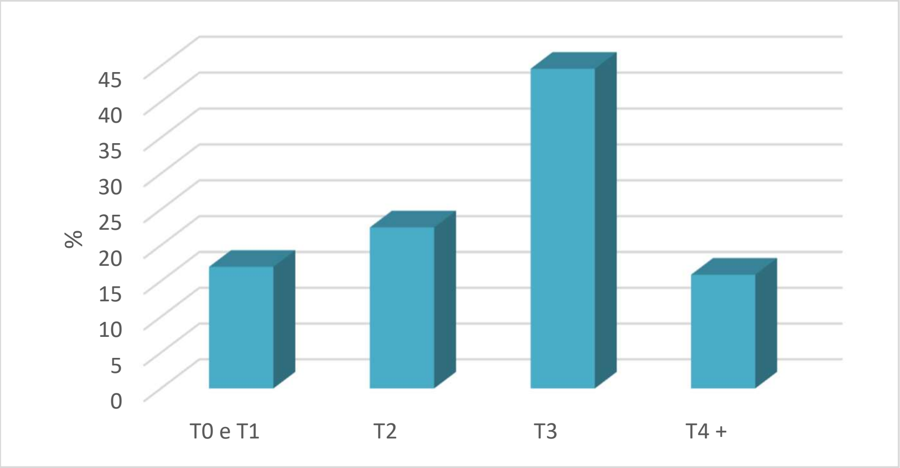

Figure 2.1 - Portuguese households by typology [11]

The construction reality has been changing through the years, with more attention being lately given to energy-efficient architecture, improving the thermal performance and luminous necessities of the buildings.

According to recent data we can see that most current buildings were built between the years of 1971 and 1990, with 1,167,703 residential buildings built in that period [12], as seen in Figure 2.2.

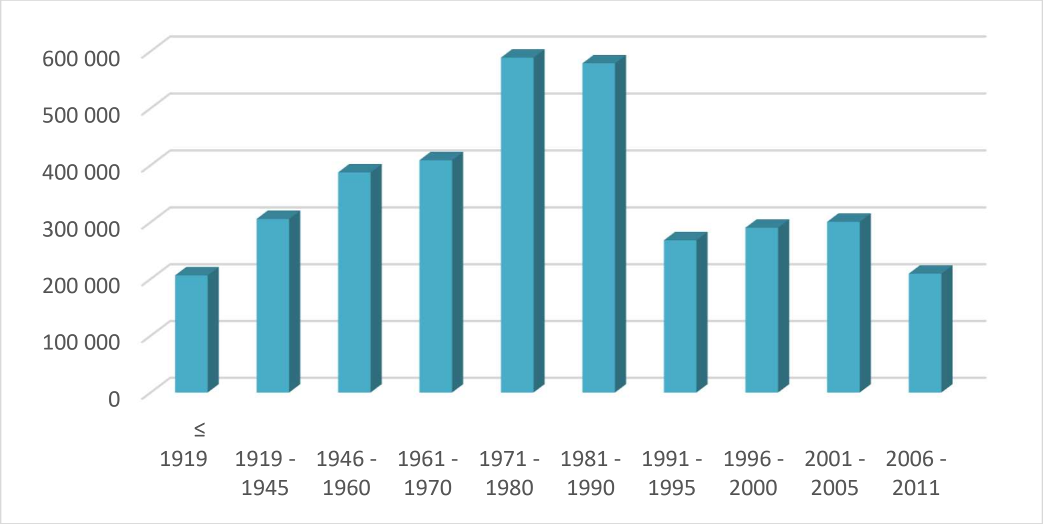

Figure 2.2 - Portuguese buildings by year of construction [12]

In Figure 2.3 it is possible to see that around 27% of the total residential buildings in Portugal in the year of 2018 need some sort of refurbishment [11]. About 35% of these renovations are medium or major scale [11], as seen in Figure 2.4. This information highlights the potential need of implementing new energy efficiency measures in the existing building stock, mostly constructive technologies, but also other types of technologies.

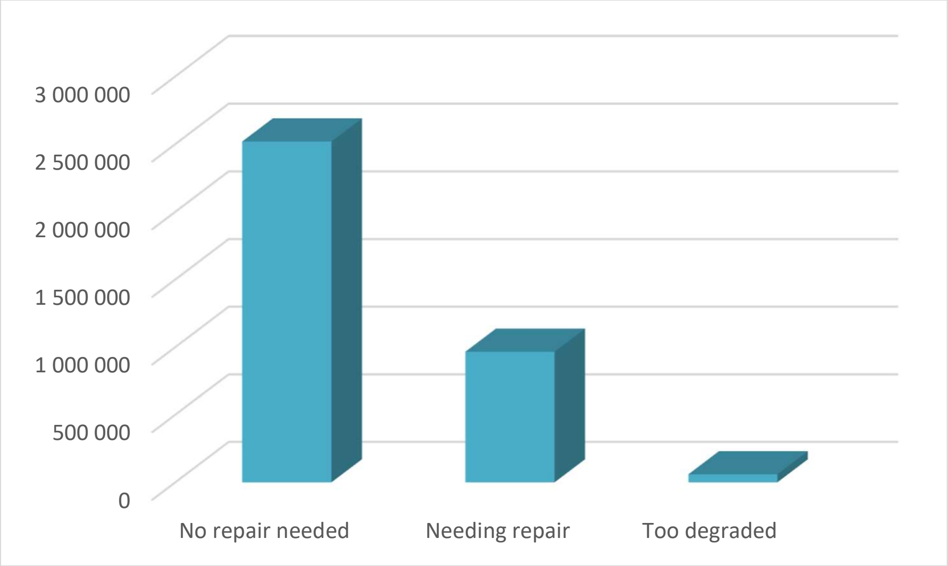

Figure 2.3 - Portuguese buildings that require refurbishment [11]

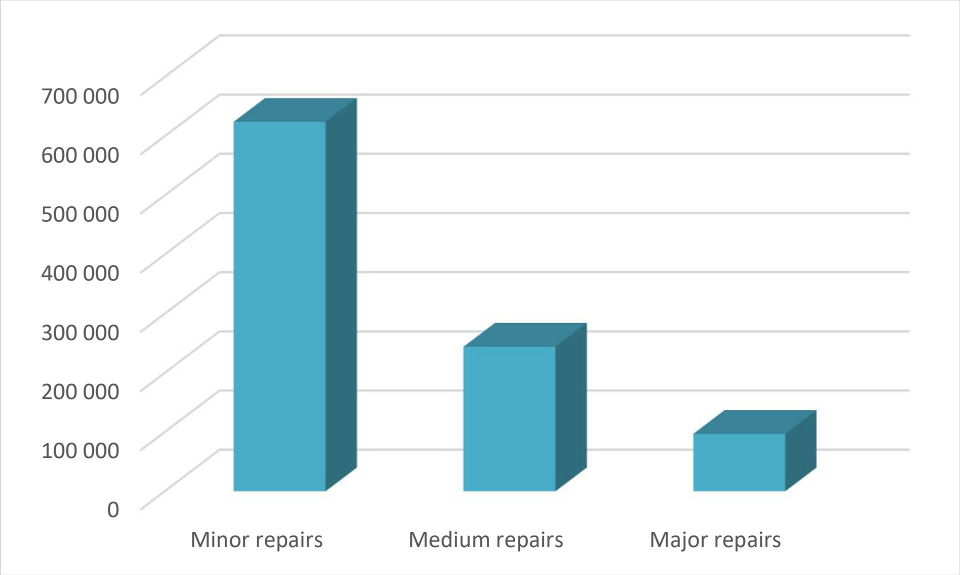

Figure 2.4 - Portuguese buildings per type of refurbishment needed [11]

Regarding the measures related to constructive technologies, it is also important to investigate the refurbishment necessities of the building stock. The main refurbishment necessities on this type of buildings are usually in the roof and façade. This is important since wall and roof insulation are energy efficiency measures with high impact. Data on insulated houses in Portugal reveal that only 21.1% of the households have façade insulation, and 17.1% have roof insulation. According to the latest data, there are 1,169,591 buildings needing repair in the roof and 1,256,094 in the façades [13].

Another important constructive issue is the type of window glazing used in the buildings. According to the recent statistics, most windows are single glazed. However, double glazed windows can have a big impact in maintaining the desired thermal comfort inside the building, reducing the energy demand for heating and cooling systems [13].

Table 2.1 - Portuguese building's glazed façades by type of glaze in 2011 [13]

TYPE OF GLAZE	SOUTH FACING FAÇADES	EAST FACING FAÇADES	WEST FACING FAÇADES
SINGLE GLAZED	74.9%	71.7%	71.8%
DOUBLE GLAZED WITHOUT THERMAL CUT	19.2%	23.2%	23.3%
DOUBLE GLAZED WITH THERMAL CUT	7.2%	6.1%	6.2%

Another important concept to assess the energy efficiency potential of the residential sector in Portugal is the building’s energy classification. This classification is made by ADENE (Agency for Energy) and it follows the SCE, approved by Decree-Law nº118/2013 [14].

This certification considers three major factors. The first is related to the thermal insulation, the second concerns the assessment of the efficiency of the appliances and the third the renewable energy sources that contribute to the energy consumed by the building. According to statistical data from ADENE [16], 70.6% of the existing buildings are classified as below B-, as shown in Figure 2.5. Additionally, it is also possible to observe that there is a major improvement in the overall energy efficiency after rehabilitation, as we can see in Figure 2.6, where there is represented the efficiency classification of buildings that suffered some sort of refurbishment.

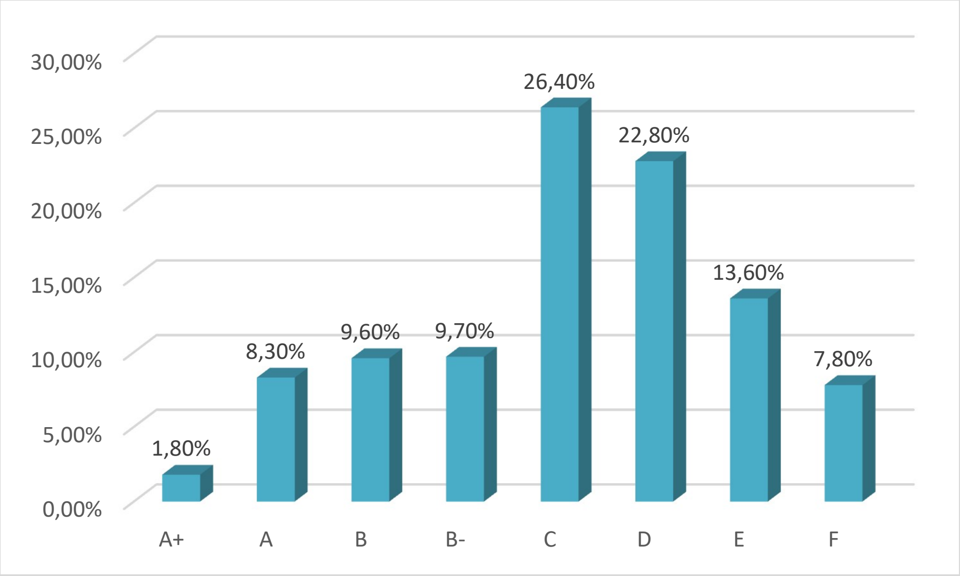

Figure 2.5 - Portuguese buildings' efficiency class adapted from [16]

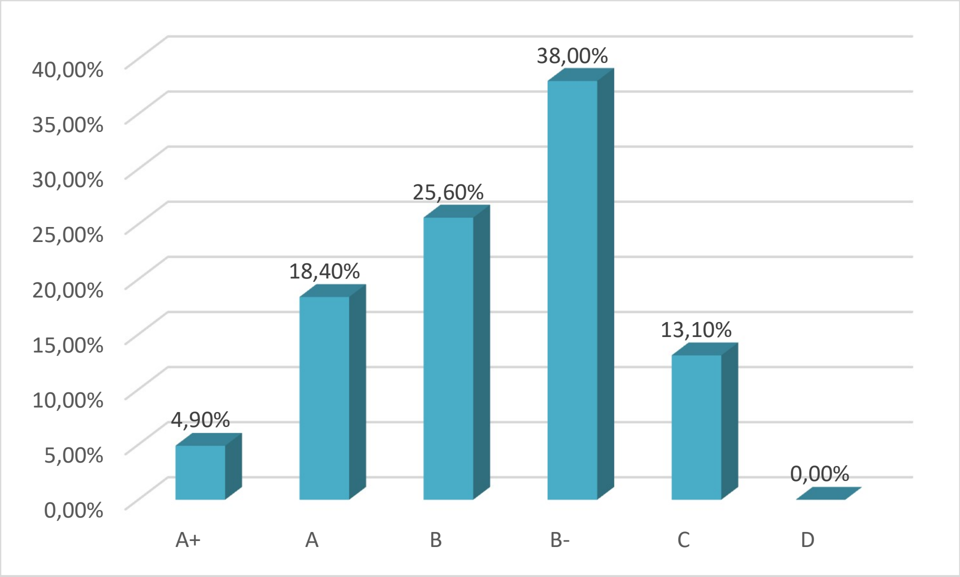

Figure 2.6 - Portuguese buildings' efficiency class after rehabilitation [16]

2.2. Energy Consumption in the Residential Sector

In order to fully characterize the residential sector in Portugal, it is important to collect data regarding the energy consumption tendencies and habits in this sector. In 2017, the residential sector was responsible for 16.4% of the total end-use energy consumption [17], corresponding to a total of 2,920,108 toe of energy consumed, divided as shown in Figure 2.7. The energy used was 420,441 toe of petrol, 274,226 toe of natural gas, 1,148,211 toe of electricity and 1,077,230 toe of non-renewable electricity sources.

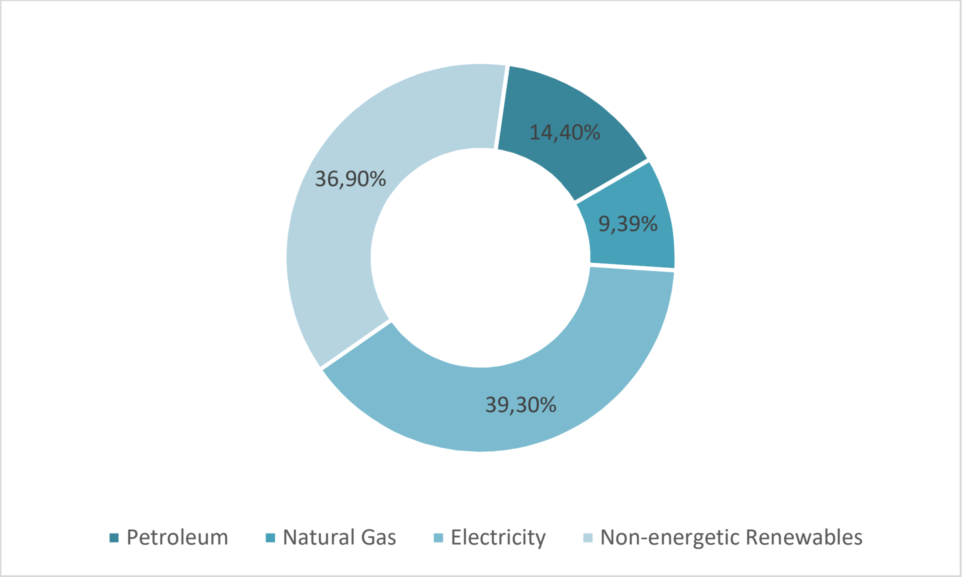

Figure 2.7 - Portuguese residential sector energy consumption by type of fuel [17]

Individually considering the end uses and as shown in Figure 2.8 space and water heating are responsible for most of the residential sector energy consumption [13]. Lighting, space and water heating and space cooling are responsible for a total of 50% of household consumption, as the other 50% are related to kitchen equipment and other electrical equipment. The latter is more related to the quantity of equipment rather than its individual consumption. However, there have been several measures and incentives to replace this equipment with more efficient options.

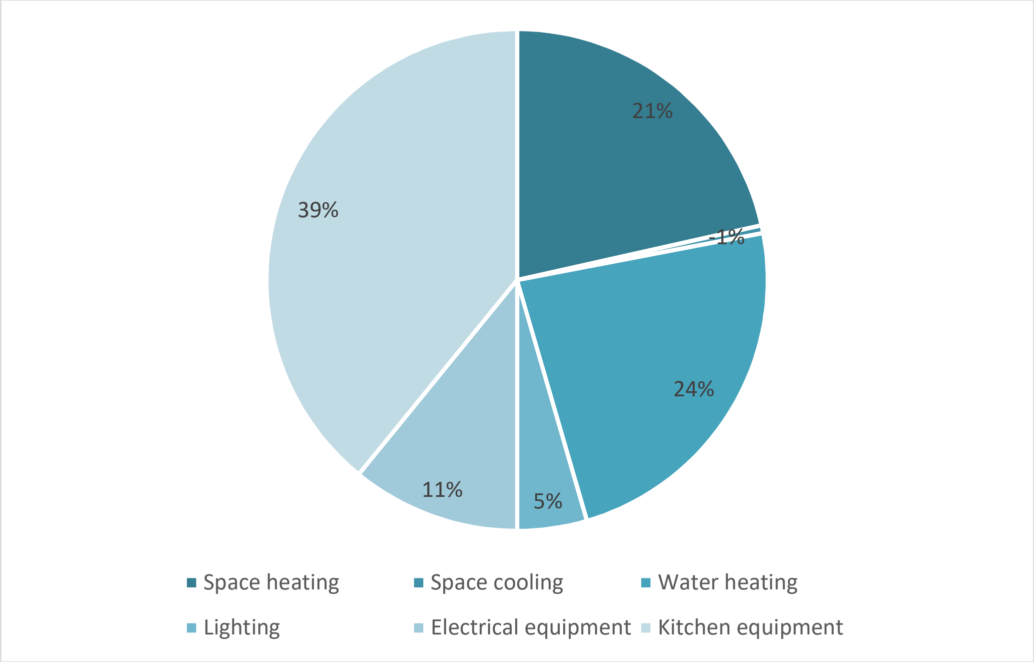

Figure 2.8 - Portuguese residential sector energy consumption by end-use [13]

2.3. Residential Building Characterization

In order to fully assess the impacts and performance of the selected measures to be supported, it is important to characterize a typical residential building in terms of thermal comfort, roof, façade and glazed area. In terms of thermal comfort, it varies in each season, and with the occupant's level of activity. We will consider the conditions during Summer and Winter, with two levels of activity: sedentary and asleep [18].

Table 2.2 - Operative comfort temperature [18]

	WINTER	SUMMER
ASLEEP	14ºC	30ºC
SEDENTARY	16ºC	28ºC

In terms of the building's constructive characteristics, it is important to separate them by time periods, since architecture and construction methods are in constant change, and different types of residential buildings: single-dwelling and multi-dwelling buildings.

2.3.1. Single-dwelling Building

The single-dwelling building was considered to have one floor until 1991, where the typical panorama on the type of construction changed into a two-floor building, reducing the roof area but increasing the façade area. The evolution of the glazed area, also increased, revealing the awareness for the importance of using natural light and air flow to reduce the house energy consumption [18].

The typical building scheme for every era considered is shown in Figure 2.9 to Figure 2.12,. The building characteristics in terms of roof, façade and glazed areas are detailed in Table 2.3.

Table 2.3 - Typical Portuguese single-dwelling residence characteristics by era [18]

ERA	≤1960	1961-1990	1991-2012	≥2013
FLOORS	1	1	2	2
FAÇADE WALL AREA	21.1	23.3	19.9	20.4
GLAZED AREA	3	3.75	7.75	8.25
ROOF AREA	79.9	100	77.4	82.4

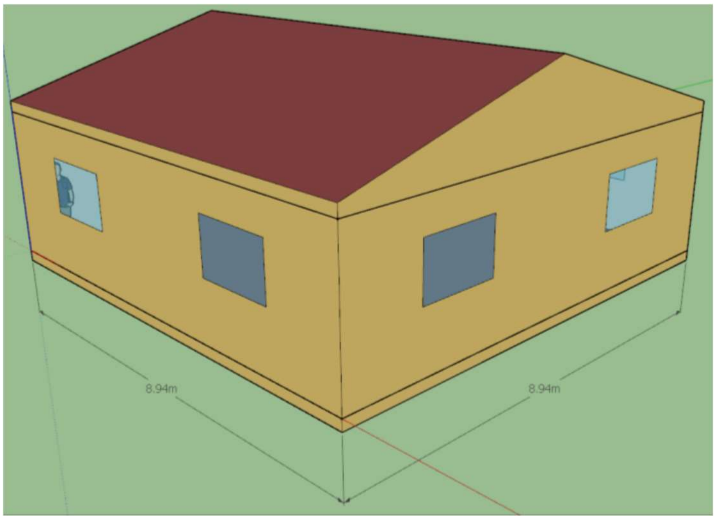

Figure 2.9 - Single-dwelling building (until 1960) [18]

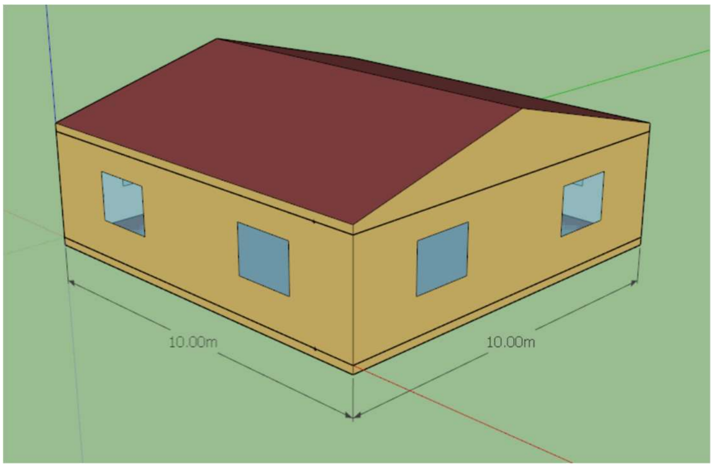

Figure 2.10 - Single-dwelling building (from 1961 to 1990) [18]

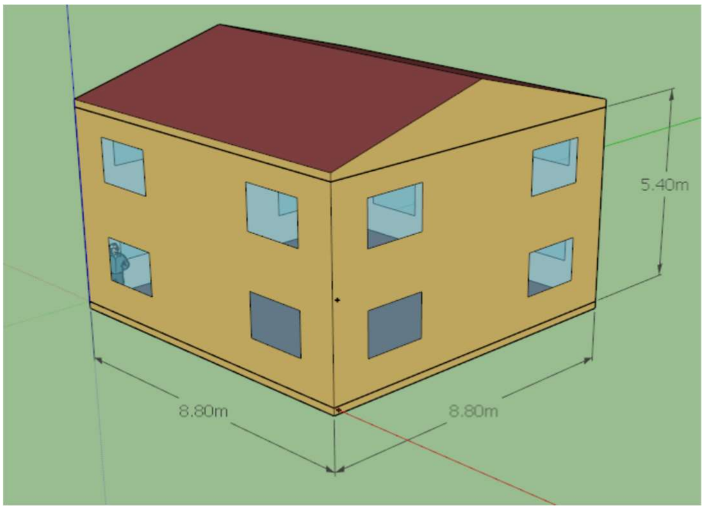

Figure 2.11 - Single-dwelling building (from 1991 to 2012) [18]

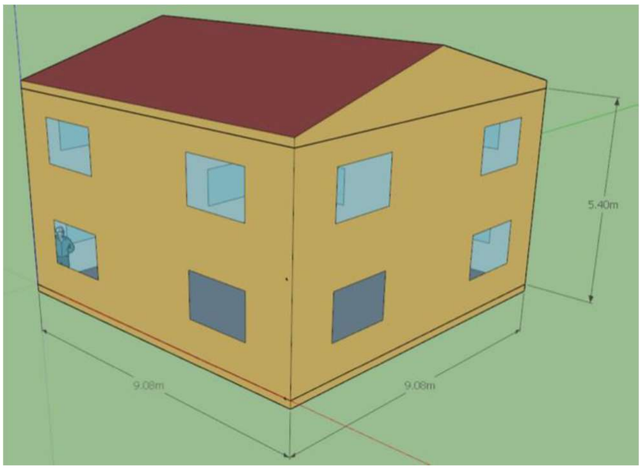

Figure 2.12 - Single-dwelling building (from 2013) [18]

2.3.2. Multi-dwelling Building

For multi-dwelling buildings, two types of buildings were considered, facing North/South and East/West, both with three floors. In total, each building consists of 12 residences, with two outer façades or two outer façades and roof. The main difference across the eras of construction found is the glazed area [18]. The typical multi-dwelling residence schemes are shown in Figure 2.13 and Figure 2.14, and its characteristics are detailed in Table 2.4

Table 2.4 - Typical Portuguese multi-dwelling residence characteristics by era [18]

	2 OUTER FAÇADES				**2 OUTER FAÇADES AND COVER**			
ERA	**≤1960**	**1961-1990**	**1991-2012**	**≥2013**	**≤1960**	**1961-1990**	**1991-2012**	**≥2013**
FAÇADE WALL AREA	11.5	11.9	12.9	12.6	11.5	11.9	12.9	12.6
GLAZED AREA	4.93	5.12	6.96	8.37	4.93	5.12	6.96	8.37
COVER AREA					65	70	95	105

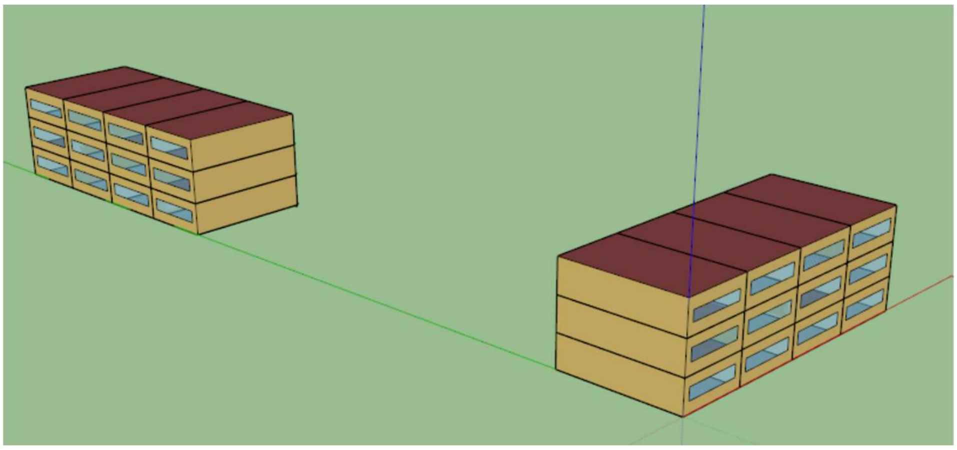

Figure 2.13 - Multi-dwelling building (until 1960) [18]

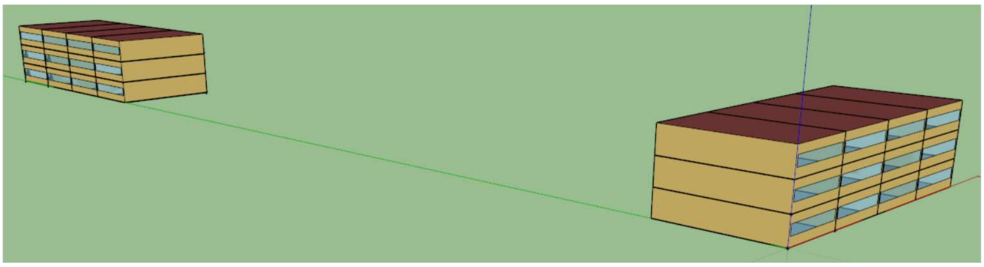

Figure 2.14 - Multi-dwelling building (from 1991 to 2013) [18]

3. THE GENETIC ALGORITHM (GA)

Genetic optimization is a computing method based on the Darwinian principle of reproduction and survival of the fittest. The genetic algorithm moves towards the optimal solution to a problem by genetically evolving a population of individuals over a series of generations. Each individual of this population represents a possible solution to the problem in study, and each of these individuals is associated with a fitness value, given by the fitness function. The fitness function allows assessing every individual according to the different evaluation axis (objectives), also taking into consideration constraints or any other aspect the practitioner thinks are useful/necessary. The population is then transformed over a selected number of generations, using reproduction, crossover and mutation [19]. The offspring individuals inherits the parent's characteristics and by crossover and mutation acquire new ones. If they perform better than their parents, they have a better chance of surviving. Each individual is composed of genes, representing decision variables or other characteristics, which combine into a string to form a chromosome.

Genetic algorithms can be described in the following steps, represented in Figure 3.1:

1. Generate an initial population of, for example, random individuals.
2. Assign a fitness value to every individual in the population, using the fitness functions and variable constraints, and perform the following steps iteratively, until reaching the stopping criteria:
    a. Crossover: create new individuals from existing individuals, by randomly recombining genes from their chromosomes.
    b. Mutation: randomly mutation occurs in some genes of some individuals, this way creating new genetic material.
    c. Reproduction: create a new population with new individuals. Fitter individuals are more likely to reproduce more.
3. Once reached the stopping criteria, select potential solutions amog the non-dominated individual.

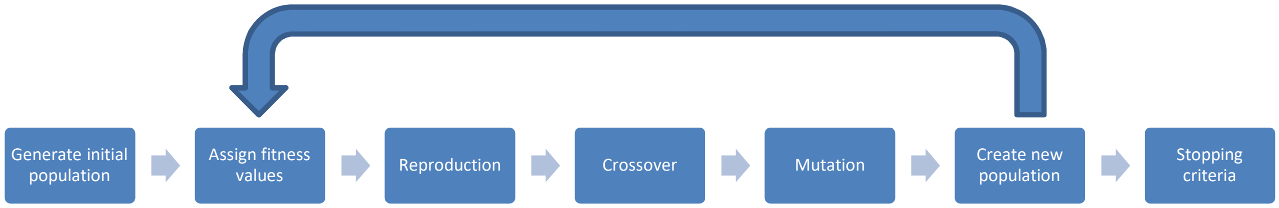

Figure 3.1 - Schematic representation of the GA functioning

3.1. The NSGA-II (Non-dominating Sorting Genetic Algorithm)

The NSGA-II is a genetic algorithm, and it is frequently used in multi-objective problems, as the one we are dealing with in this work.

The steps followed by the algorithm selected for this work and briefly presented above, are described in detail in the following sub-sections.

3.1.1. Initial Population

The initialization process of the genetic algorithm consists of creating a series of chromosomes, which can be binary strings, vectors of integer numbers or vectors of real numbers, or any combination of integer/real numbers. These strings are the representation of the individuals that compose the population of the algorithm. Each one of these strings is a potential solution for each variable in the problem, and the initial population is created by assigning random values to these variables, within the upper and lower limits defined by the user. In our case, the population can be represented in the form of a matrix, with n individuals composed by m genes.

$$\begin{bmatrix} x_{1,1} & \cdots & x_{1,m} \\ \vdots & \ddots & \vdots \\ x_{n,1} & \cdots & x_{n,m} \end{bmatrix}$$

3.1.2. Fitness Evaluation

In the NSGA-II, the fitness evaluation scheme is based on Pareto dominance relation. In this case, the best rank (Rank 1) is assigned to all non-dominated individuals, and these individuals are tentatively removed from the current population. Within the remaining population, Rank 2 is assigned to all non-dominated remaining individuals and then tentatively removed, repeating this process for the next ranks until all individuals in the population have a rank assigned. This ranking scheme will be the primary criterion in the binary tournament selection for parent selection [20].

3.1.3. Tournament Selection

This phase of the algorithm selects individuals from the current population to be a parent using the tournament selection phase. A set of random individuals are selected to compete against each other. The first selection criterion is the individual's rank, where the solution with higher rank is selected as a parent. If the rank of each individual is the same, the algorithm uses the second selection criterion, called the crowding distance. This means that the individuals positioned in a less crowded region in the objective space are selected as a parent. This tournament process is repeated until the new population is the same size as the initial population [21].

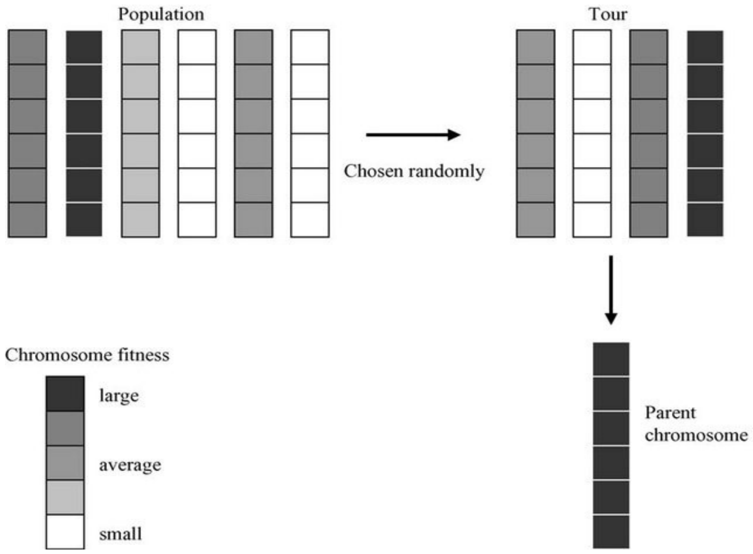

Figure 3.2 - Tournament selection [21]

3.1.4. Simulated Binary Crossover

Crossover is a genetic operator used in Genetic Algorithms in order to recombine the genetic information of two or more individuals. In the simplest approach, after selecting two parents, data from a selected point of the string of the individual is swapped between both individuals, in order to create two offspring solutions with genetic information from both parents. This genome recombination can happen in one (single-point crossover), two (two-point crossover) or multiple (multi-point crossover) points of the parents.

The SBX operator is a type of single-point crossover that uses two parent vectors and apply the blending operator variable by variable to create two offspring solutions. This operator uses a parameter, the distribution index, which has a direct effect in controlling the spread of the offspring solutions. This index is kept fixed, and a higher value results in offspring solutions close to the parents, while a low value results in offspring solutions in zones further from the parents.

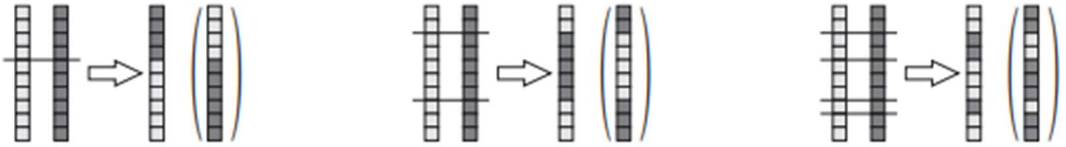

Figure 3.3 - Single binary crossover [22]

3.1.5. Polynomial Mutation

The polynomial mutation works with three user selected parameters: the mutation probability P_m, the distribution index η_m and the number of decision variables n. Each decision variable x_i upper and lower bounds are defined by $[x_i^l, x_i^u]$, and each one of these variables has a probability P_m to be mutated. The process of the polynomial mutation is given by the following algorithm:

```
$i = 0$
    $repeat$
        $r = U[0,1]$
        $if\ r \le P_m\ then$
            $\delta_1 = \frac{x_i - x_i^l}{x_i^u - x_i^l}$
            $\delta_2 = \frac{x_i^u - x_i}{x_i^u - x_i^l}$
            $r = U[0,1]$
            $\delta_Q = \begin{cases} [(2r) + (1-2r) \times (1-\delta_1)^{\eta_m+1}]^{\frac{1}{\eta_m+1}} - 1 & , r \le 0.5 \\ 1 - [2(1-r) + 2(r-0.5) \times (1-\delta_2)^{\eta_m+1}]^{\frac{1}{\eta_m+1}}, & r > 0.5 \end{cases}$
            $x_i = x_i + \delta_q . (x_i^u - x_i^l)$
        $end$
                        $until\ i++= n$
```

This algorithm produces an offspring with randomly mutated genes from its parent, based on the mutation probability and distribution index. The mutation strength varies according to the distribution index. Lower η_m values produce stronger mutations, resulting in solutions that are far away from the parent solution, while lower values produce solutions closer to their parents.

3.1.6. Stopping Criteria

One of the most commonly used stop criterion for the NSGA-II is the number of generations. A generation is complete when a new population, created through the selection and genetic operators, is formed. The ideal number of generations varies from problem to problem, and it is usually defined by trial and error, finding the point where few changes to the population are verified.

4. ENERGY EFFICIENCY MEASURES

The energy efficiency programs addressing the residential sector generally support different types of measures, depending on the energetic profile and characteristics of the building stock.

The selected measures can be divided in two groups: constructive measures and technological measures. The constructive measures focus on construction materials and strategies that can be applied in refurbishment operations, such as insulation and window replacement, in order to improve the building's thermal performance. The technological measures focus on replacing the existing technologies such as lighting, air heating, and domestic water heating, with more efficient solutions.

4.1. Selected Measures

The selection of measures to be included in the energy efficiency portfolios was done according to the Portuguese building stock renovation necessities and to the measures previously supported by Portuguese energy efficiency programs, specifically PPEC 2017/2018 [23].

The measures supported by PPEC 2017/2018 addressed the replacement of equipment with more efficient options. Therefore, the technological measures that will be further described in the next sections are based on [24], whereas the selected constructive measures are based on [25].

4.1.1. Constructive Measures

In order to assess the environmental and energy impacts associated with the application of different types of insulation, as XPS (Extruded Polystyrene Foam) or EPS (Expanded Polystyrene Foam), we consider the characteristics of the Portuguese building stock (see Section 2.3). These measures are indexed according to Table A.12.

We assume, by default, that the existing business as usual (BAU) heating and cooling systems prior to the adoption of the corresponding best available technologies (BAT) are natural gas boilers for heating and electrical cooling. The impacts of the constructive measures in the temperature control in terms of energy savings, quantified based in the BAU energy consumption in each end-use, are [24]:

- Heating
    - 68.5% for insulation application
    - 66.1% for window replacement
- Cooling
    - 31.5% for insulation application
    - 33.9% for window replacement

These values were considered for all the different types of building studied.

35mm XPS Insulation

This insulation material is usually sold in plaques and applied to cavity walls. The calculations of the lifecycle impact of this product were based on its Environmental Product Declaration, which contains the reference values to 1m^2 of XPS [26].

35mm plaques have a thermal conductivity of 0.035 W/(m.K), which represents a density (ρ) of 32 kg/m^3. The reference values of the environmental declaration are 33.7 kg/m^3, referred to as a 1 m^2 plaque with a thickness of 100 mm. It is, however, possible to calculate the adapted value for the LCA indicator for the 35mm plaques used in this analysis, using the following expression, where I_{adap}, d_{adap} and ρ_{adapt} are the adapted LCA indicator, board thickness and density, respectively, and I_{ref}, d_{ref} and ρ_{ref} are the reference values for the same parameters:

$$I_{adap} = I_{ref} \times \frac{\rho_{adap}}{\rho_{ref}} \times \frac{d_{adap}}{d_{ref}}$$

The value computed for the "cradle-to-gate" GWP is 3.14 kgCO$_{2eq}$/m^2, and the transport from the gate to the site has an impact of 0.094 kgCO$_{2eq}$/m^2. Finally, the end of life stage has an impact of 3.799 kgCO$_{2eq}$/m^2, resulting in a lifecycle impact of 6.939 kgCO$_{2eq}$/m^2.

110mm EPS Insulation

The Expanded Polystyrene foam is a light weight, tough, strong and rigid thermoplastic insulation foam, whose density varies from 18 to 22 kg/m^3. The lifecycle assessment (LCA) of this product is based on its Environmental Product Declaration, where the impacts of 1 m^2 of EPS, with a thermal conductivity of 0.031 W/(m.K) are revealed [27]. The “cradle-to-gate”, transportation and assembly represent a total impact of 67.07 $kgCO_{2eq}/m^2$. At the end of the life stage of this product, two different scenarios were studied:

- 100% of the product is processed and incinerated, resulting in benefits for thermal energy and electricity, which represents a total impact of 33.63 $kgCO_{2eq}/m^2$;
- 100% of the product is processed and recycled resulting in a reduction of 33.27 $kgCO_{2eq}/m^2$ of the global lifecycle impacts.

PVC frame double-glazed window

When analysing the best option for the building material of the window frame, the choice was PVC, due to its lower impact during the production phase, when comparing to other usable materials, like aluminium.

The basis for the calculations of the lifecycle impact of this technology was the environmental declaration of the product, which provides the values of the impact of one double-glazed window, with an area of 1.82m^2 [28]. During the manufacturing phase, it is considered the “cradle-to-gate” impacts, as well as the transport from the gate to the installation site, and the assembly of the window itself. Therefore, the impact of the manufacturing of one 1.82 m^2 double-glazed window with a PVC frame is 118.778 $kgCO_{2eq}$. In the use stage of this technology, the net heat losses caused by the windows are considered, as well as the replacement and renovation of individual components, due to shorter technical life than the window itself.

At the end of the operating life of the window, 95% of its components can be collected and recycled, which causes a significant positive impact in the overall lifecycle assessment of the product. This impact reflects on a reduction of 34.8 $kgCO_{2eq}$ on the entire lifetime emissions of one window. The disposal of the materials that cannot be recycled represents an impact of 10.688 $kgCO_{2eq}$.

4.1.2. Technological Measures

The energy savings during the use phase of the technologies used in the following measures were obtained according to the results from the literature [23], [24] and [25], in order to consider the Portuguese energy mix.

In terms of technology selection, potential effects in terms of power requirements in consumer installations were not considered.

Measure nº 45: Replace CFL (compact fluorescent lamp) with LED (light-emitting diode) lighting

The replacement of CFL illumination with LED illumination has already been happening for some years, due to the awareness towards the higher efficiency of LED illumination. However, CFL luminaires are still the most common type of illumination in Portuguese households, revealing that it is still important to encourage the implementation of this measure.

In order to assess the lifecycle impacts of this measure, the study on which it is based adopted a functional unit of 1 lux (1 Lumen/m^2), for an operating time of 50,000 hours. The impact can be divided into three separate periods: production, use and end of life [29].

The production impact of the CFL is 0.0482 $kgCO_{2eq}/m^2$, while the LED impact is 0.134 $kgCO_{2eq}/m^2$. LED has a lifetime of 50,000 hours, while CFL only has 10,000 hours. Knowing this, in the lifecycle assessment, 4 maintenance stages were considered for the CFL, replacing the lamp.

Measure nº 46: Replace halogen lamps (42W) with LED lighting (8W)

The production impact analysis for these technologies was based on the OSRAM data, revealing an impact of 0.3285 $kgCO_{2eq}$ for the halogen lamp [30] and 2.4 $kgCO_{2eq}$ for the LED [31]. However, the LED has an average operating lifetime of 25,000 hours, while the halogen lamp has only 2,000 hours. So, for the same operating time, the production impact of the halogen lamp is 4.12 $kgCO_{2eq}$.

Measure nº 47: Replace Domestic Electric Storage Water Heater with Solar Heater with Electric Backup

Thermosyphon solar heating systems supply hot water at a temperature of about 60ºC, and consist of a collector, storage tank and connecting pipes. In a Mediterranean area, these systems usually consist of two flat-plate solar collectors, with an absorbing area between 2.5 to 4 m^2 and a storage tank with a 150 to 180 litres capacity. These systems also have an auxiliary electric immersion heater used in winter during periods of low solar insulation. In this lifecycle analysis, the selected functional unit is the production of one of these systems, with 2 panels of 2.7 m^2, a 150 litres capacity and a 3 kW auxiliary electric heater. The embodied energy of one panel is 2.663 GJ, and for the construction of the remaining parts it is 1.4323 GJ. For this system, if we also consider the embodied energy during installation, this represents an embodied energy of 6.946 GJ [32].

Measure nº 48: Replace Natural Gas Boiler with a Heat Pump (5kW)

A natural gas boiler generates thermal energy, which proves to be very demanding in terms of resources and energy, and not as efficient as a heat pump. An air-source heat pump consists of a device that transfers air from a heat source to a heat sink, using electrical power. In this type of technology, the heat transfer is higher than the consumed energy, proving its higher efficiency.

The comparative lifecycle assessment used as a base for the work of [33] used the United Kingdom production mix, which is mostly composed of fossil gases. This fact might help explain the high GHG emissions of heat pumps. The heat pump has a "cradle-to-grave" impact of 0.276 kgCO$_{2eq}$/kWh, while the natural gas boiler has an impact of 0.220 kgCO$_{2eq}$/kWh. The use phase of these technologies represents 95% of the emissions of each product, and the end of life phase was not relevant enough to be considered in the assessment.

In this study, the lifecycle impact was calculated for 1,250 operating hours through a lifetime of 15 years.

Measure nº 49: Replace Natural Gas Boiler with Biomass Boiler (Pellets)

The data used for the calculation of the lifecycle impacts of the natural gas boiler is the same as mentioned above [33].

In the case of the biomass boiler, the LCA assessment studied in [34] used as functional unit (FU) the production of one biomass boiler with a rated output of 46 kW, produced and operating in Italy for a lifetime of 15 years.

The lifecycle impact of this technology, in terms of GWP is 21,664.2 kgCO$_{2eq}$, where 98.7% of that value represents the operation phase, 0.74% the manufacturing stage, 0.34% the transportation and installation and 0.22% the end of life stage. It is also important to refer that, in this study, it was considered that 83% of the energy spent in the lifecycle of the product is obtained from non-renewable energy sources.

Measure nº 50: Replace Domestic Electric Storage Water Heater (2kW) with a Heat Pump (5kW)

The data for the lifecycle assessment of this measure is the same used for previous measures using these technologies ([33], [35]).

4.2. Energy Efficiency Measures Lifecycle Characterization

After obtaining the lifecycle performance of each measure, it is necessary to characterize it in terms of cost, emissions during each period of its lifetime and energy savings. The GWP emissions were calculated taking into account the Portuguese scenario, in terms of the energy mix, considering the year of 2019 [36] and emission factors in the year of 2017 [37], which are detailed in Table 4.1.

Table 4.1 - Portuguese energy mix and emission factor

ENERGY SOURCE	PENETRATION	GWP EMISSION FACTOR (KGCO2EQ/KWH)	EMISSÕES (KGCO$_{2EQ}$/GJ)
COAL	19.60%	0.82	0.16
NATURAL GAS	18.10%	0.49	0.09
HYDRO	23.70%	0.02	0.01
WIND	22.00%	0.01	0.00
BIOMASS	5.00%	0.23	0.01
SOLAR	1.50%	0.05	0.00
FOSSIL CHP	8.10%	0.52	0.04
GEOTHERMAL	0.40%	0.04	0.00
FUEL-OIL	1.60%	0.28	0.00
TOTALS	**1**		**87.91**

This characterization also includes the end-of-life stage of the equipment, so it is necessary to consider the possibility of recycling the materials. In order to fully characterize each measure in this stage, a recycling rate was considered for each type of material, based on Portuguese recycling rates. The constructive materials have a recycling rate of 28% while electronic equipment has a recycling rate of 44% [38].

Table A.1, where A refers to the Annexes section, details each lifecycle assessment measure (indexed according to Sections 4.1.1 and 4.1.2), in terms of the initial costs for the program, embodied GWP emissions, energy savings and avoided emissions during the use-phase and throughout the entire lifetime.

4.3. Energy Efficiency Measures Performance

The performance of each measure was also evaluated according to several other indicators. The selected indicators are the Savings to Investment Ratio (SIR), the Payback Time (PBT), the Energy Payback Time (EPBT) and the Carbon Payback Time (CPBT). The performance of each measure in the selected indicators is detailed in Table A.2.

The selected indicators are further explained in the next sub sections.

4.3.1. SIR

This indicator represents whether the savings of implementing a measure justifies the initial investment. It can be seen as the ratio between the lifetime savings of a technology over the initial investment to implement it. Therefore, in terms of this indicator, the higher the better. To calculate the savings throughout the lifetime of the equipment, it is necessary to consider the discount rate, which refers to the rate of return used to discount future cash flows to their present value. The discount rate used in this work is 5 %, the value used in PPEC 17/18 [39]. The SIR is then calculated using the following formula [10]:

$$SIR = \frac{\sum_{t=1}^{T} \frac{Yearly\ Savings}{(1+d)^t}}{Initial\ Investment}$$

Where T represents the lifetime of the equipment and d represents the discount rate.

4.3.2. PBT

The PBT is the time required to recover the initial cost of an investment. In the specific case of this work, it represents the number of years it would take for the energy saving obtained by implementing a determined measure, represented in monetary value, to cover the initial investment on that measure. In terms of payback indicators, it is desired to obtain the lower value possible.

This ratio is calculated using the following formula:

$$PBT(years) = \frac{Initial\ investment(€)}{Annual\ cash\ inflows(€)}$$

4.3.3. EPBT (Local and Global)

The EPBT is calculated in a similar way as the regular PBT. However, in this case, it considers the embodied and saved energy of an energy efficiency measure, instead of the cash flow produced by it. In this work, two types of EPBT were calculated, with two different approaches: locally and globally. The difference between these two approaches is in the fact that the equipment and construction materials used and implemented in the selected measures are not produced in Portugal. So, in a local approach to the EPBT, the cradle-to-gate phase is not considered, contemplating only the end-of-life phase. In a global approach, both phases are considered in the calculations. These indicators are calculated using the following formulas:

$$EPBT\ (Local)(years) = \frac{End\ of\ Life\ Energy\ (GJ)}{Annual\ Energy\ Savings\ (GJ)}$$

$$EPBT\ (Global)(years) = \frac{Cradle\ to\ Gate\ Energy\ (GJ) + End\ of\ Life\ Energy\ (GJ)}{Annual\ Energy\ Savings\ (GJ)}$$

4.3.4. CPBT

The CPBT also follows the standard PBT concept, while considering the embodied GWP (Global Warming Potential) emissions. It calculates the number of years it would take for the emissions avoided by implementing an energy efficiency measure to match the emissions originated by its production and disposal. This indicator can be represented as the following ratio:

$$CPBT\ (years) = \frac{Cradle\ to\ Gate\ Emissions\ \left(kgCO_{2eq}\right) + End\ of\ Life\ Emissions\ (kgCO_{2eq})}{Annual\ Avoided\ Emissions\ (kgCO_{2eq})}$$

5. METHODOLOGY

Portfolio selection problems can be seen as multi-objective optimization problems, where a compromise between the rate of return and risk is sought [10]. The selected method to solve this sort of optimization problems was based on the NSGA-II with tournament selection, single binary crossover, and polynomial mutation, proposed by Deb et. al. [40]. The first step of the procedure consists of selecting the indicators to be used as objectives in the mathematical model. Finally, it is necessary to tune the parameters of the algorithm in terms of generations and genetic operators.

5.1. Selection of the objective functions

The selection of these objectives was based on the model suggested by Vivek et. al. [10] to evaluate energy efficiency portfolios based on a lifecycle approach. It was also considered the correlation between the results of the performance measures on the different indicators considered, which can be verified in Table 5.1. In this table, two additional indicators are included: the Energy Savings (ES) and the Embodied Energy (EE) associated to each measure.

Table 5.1 - Indicators' correlation table

	PBT	*EPBT (Local)*	*EPTB(Global)*	*CPBT*	*SIR*	*ES-EE*	*EE*
PBT	1						
EPBT (Local)	0.012118	1					
EPTB(Global)	0.726641	0.674908	1				
CPBT	0.595434	0.50767	0.721155	1			
SIR	-0.62187	-0.18306	-0.55077	-0.49758	1		
ES-EE	-0.47659	-0.10484	-0.39846	-0.35071	0.575633	1	
EE	0.263048	0.576313	0.616139	0.43364	-0.32295	0.140698	1

Based on this, three objectives were selected, in order to evaluate the portfolios not only economically, but also considering their lifecycle energetic and environmental performance:

- Return objective: maximizing the SIR, in order to ensure that the investment on the portfolio will be returned as soon as possible, through the savings related to the implementation of the portfolio of measures.
- Liquidity objective: minimizing the EPBT, as an energetic and environmental objective, in order to create portfolios on which the energy savings and decreased emissions cover the cradle-to-gate and end-of-use energy use and emissions in the quickest way possible.
- Risk objective: maximizing the minimum difference between the energy saved and the embodied measure. As suggested by Vivek et. al. [10], this measure ensures that the risk of supporting an energy efficiency measure is determined by the risk of the energy saved through the use phase of the technology implemented not covering the energy required to produce and dispose of that technology.

5.2. Mathematical Model

It is now possible to build the mathematical problem to be applied to the optimization algorithm. The first functions to be defined are the objective functions. The NSGA-II optimizes a problem toward the minimization of the objective functions, so in order to maximize the SIR, we need to apply a negative operator. Since the algorithm only develops towards the minimization of the objective functions, in order to maximize one it is necessary to minimize the negative value of that function. The first objective functions to be defined are the return function and liquidity function which are represented in the following mathematical equations as f_1, f_2 respectively:

$$f_1 = min \sum_{i=1}^{n} -(SIR_i \cdot x_i)$$

$$f_2 = min \sum_{i=1}^{n} EPBT_i \cdot x_i$$

Where SIR_i and $EPBT_i$ are the SIR and EPBT of the measure i, respectively, and x_i is the number of interventions for measure i.

One of the constraints of this problem is the budget to be applied to the selected portfolio. This budget was based on previous energy efficiency programs, specifically the PPEC 2017/2018 budget and has a value of $B = 11{,}000{,}000€$. This constraint is defined by the following function:

$$\sum_{i=1}^{n} C_i \cdot x_i \leq B$$

Where C_i is the implementation cost of measure i and B is the overall budget.

The last mathematic equation is the risk function, and as we want to minimize the risk that the energy saved in each measure is less than the energy embodied, then the objective is to maximize the minimum difference between the energy saved and the embodied energy. The solution approach used to solve this max-min optimization problem is based on the solution suggested in the literature [10]. The initial formulation for this problem is represented in the following equation, where n is the number of measures, ES_i and EE_i the energy savings and embodied energy of measure i., respectively, and x_i is the number of implementations of measure i:

$$f_3 = \max\min \sum_{i=1}^{n} (ES_i - EE_i) \cdot x_i$$

Let $v = min \sum_{i=1}^{n} EPBT_i \cdot x_i$. We want the risk function to maximize the minimum gain, which is equivalent to maximizing v where $\sum_{i=1}^{n}(ES_i - EE_i) \cdot x_i \geq v$, in order to define the upper limit of v as the minimum portfolio gain.

The mathematical formulation of the objective functions to be applied to the NSGA-II is then:

$$f_1 = min \sum_{i=1}^{n} -(SIR_i \cdot x_i)$$

$$f_2 = min \sum_{i=1}^{n} EPBT_i \cdot x_i$$

$$f_3 = \min(-v)$$

Constrained to:

$$\sum_{i=1}^{n} C_i \cdot x_i \leq B$$

$$\sum_{i=1}^{n} (ES_i - EE_i) \cdot x_i \geq v$$

The solutions are also constrained to lower and upper bounds chosen by the operator for each decision variable. In this case, the lower bound is fixed and considered 0 for every variable, since it is the lowest value that can be assumed in our specific problem, and it is intended to consider the possibility of a measure not being part of a portfolio. Regarding the upper limit, it cannot be fixed and the same to every decision variable, since the maximum number of interventions from each measure depends on its cost impact on the global budget. In this case, it was considered that the number of implementations has to be so that it does not exceed 25% of the budget, as to form the system upper limit.

5.3. Genetic Algorithm Parameterization

The selected NSGA-II tool has different parameters that need to be adequately defined in order for the tool to work well. Most of these parameters need to be tuned by trial and error, since it is the results obtained for each parametrization that gives us the information about whether the values for each parameter are adequate or not.

The first parameter requested by the algorithm is the population size, which represents the number of portfolios given as solutions. The population size depends mainly on the problem and objectives of the optimization, and for this specific case, it was considered a population of 50 solutions.

The stopping criteria in this algorithm is the number of generations, so this parameter must also be tuned by the user in order to define when the algorithm should stop running and present the final population. To tune this parameter, the algorithm was run, generation by generation, analysing the final population of each generation and marking the point when the population started suffering fewer changes, meaning that the strongest solutions were reached. Based on this method, it was defined a stopping criterion of 500 generations.

In terms of the genetic operators, both single binary crossover and polynomial mutation work based on user-defined indexes, being these parameters the crossover distribution index, the mutation distribution index and mutation probability. The tuning of these parameters was also made through trial and error, knowing that the usual values for the distribution indexes are between 20 and 100, and that higher distribution indexes generate offspring solution closer to the parents and lower values create solutions located further from the parents [41].

6. RESULTS AND DISCUSSION

The simulation was made on a machine with an Intel Core i7 CPU, with 8Gb of RAM, and it took this computer a time of approximately 5 hours to run for the selected 500 generations.

After running the NSGA-II for the objective functions and parametrization previously detailed, it was possible to obtain a final solution of 50 energy efficiency portfolios with different sizes in terms of the number of measures to be implemented. The size and constitution of each portfolio is detailed in Table A.3 to Table A.6. The visual representation of the number of implementations of each measure in each portfolio is represented in Figure 6.1, where each line refers to a different portfolio. It is important to state that the number of implementations of measures 45 and 46 are divided by a factor of 10, in order to better observe the portfolio diversity.

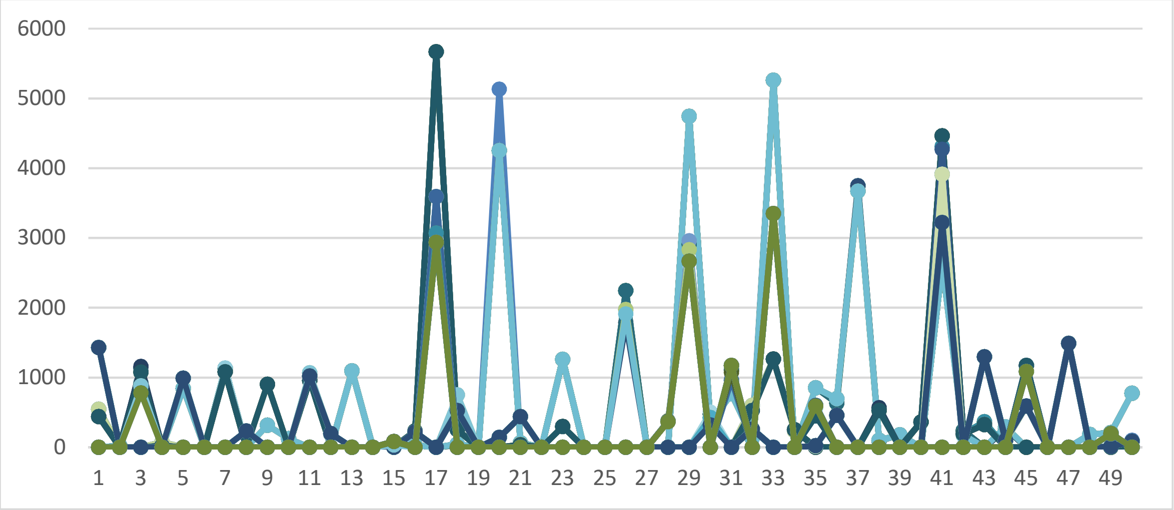

Figure 6.1 - Number of implementations of each measure (1 to 50) in each portfolio using an LCA approach.

From the visual representation given by the NSGA-II tool for the final population in function of the objectives, represented in Figure 6.2, it is possible to see the solution diversity towards the objective functions. It is also possible to identify some portfolios as non-dominated solutions, subject to further analysis, since these are the solutions with the higher rank given by the algorithm. These solutions are portfolios 1, 10, 19 and 33. These solutions dominate the remaining solutions in their proximity, revealing better performance in the objectives considered.

Portfolio 1 consists of a set of 30 measures, while portfolios 10 and 19 are composed by 20 measures and portfolio 33 by 10 measures, and the measures selected for each one of these portfolios is represented in Figure 6.3.

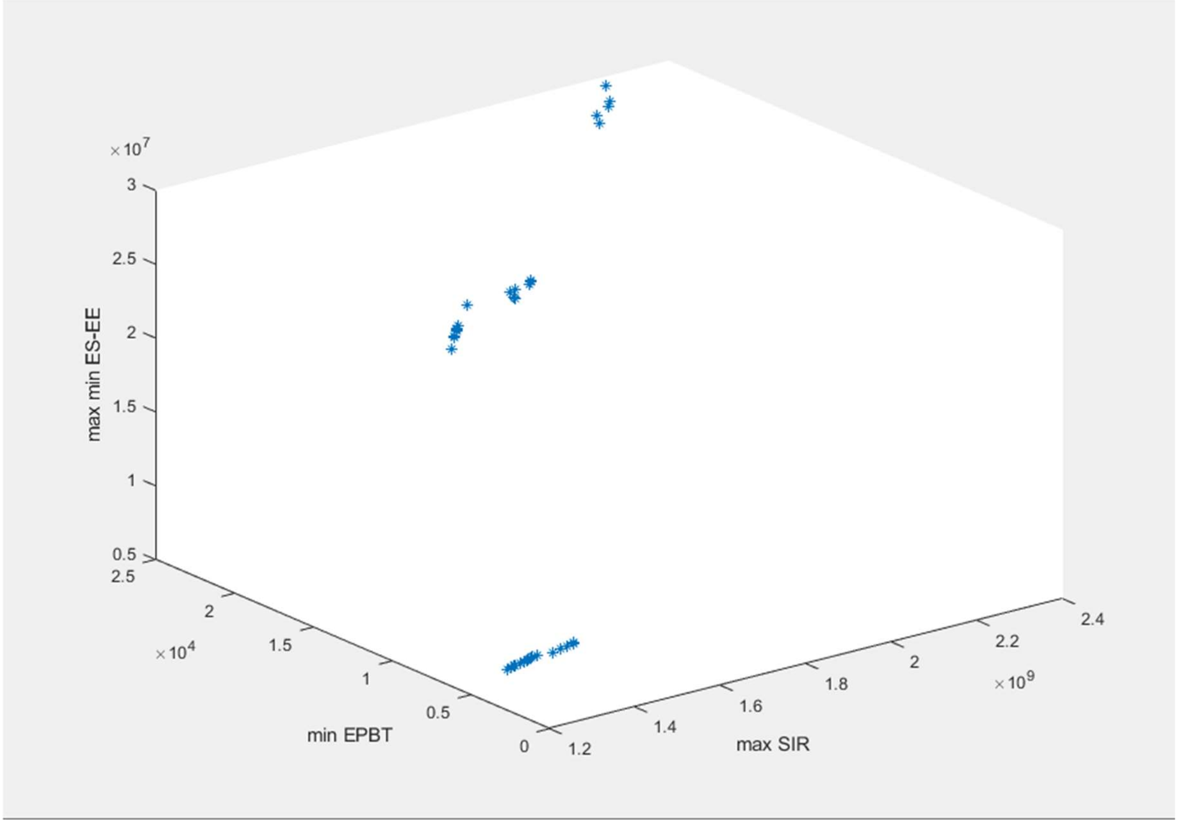

Figure 6.2 - Final NSGA-II population

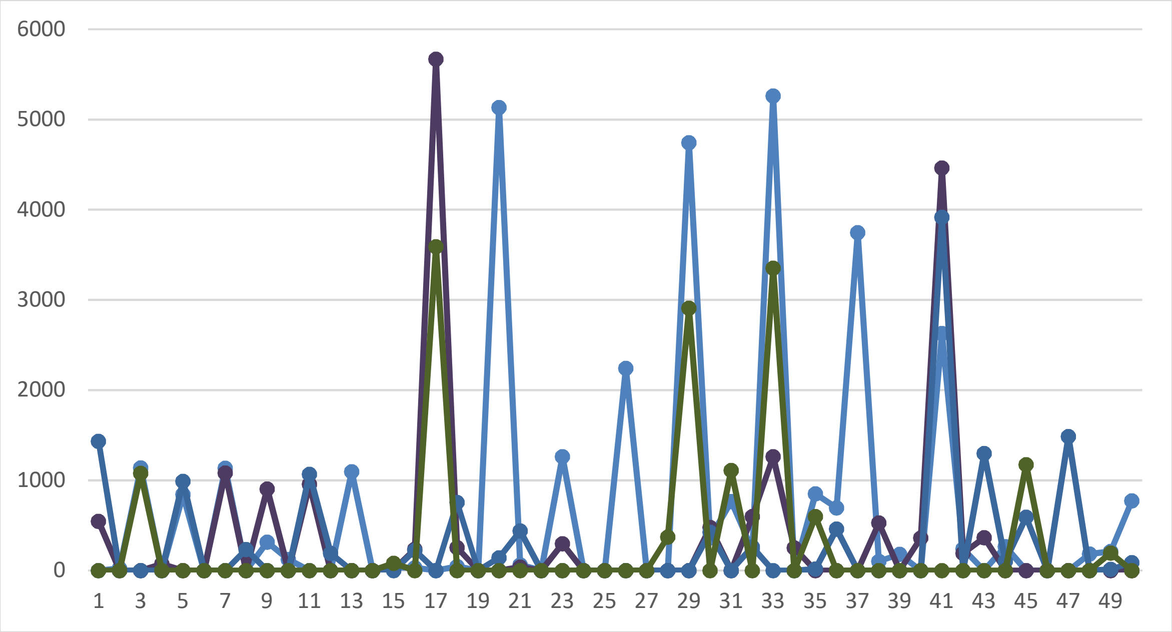

Figure 6.3 - Number of implementations of each measure (1 to 50) for the non-dominated solutions

From the results obtained, it is possible to see that there is some diversity from portfolio to portfolio in terms of measures selected, although some of the measures are present in most of the portfolios. After crossing this information with the performance of each measure according to the selected indicators for their evaluation, it is possible to conclude that the measures with stronger presence in the final population given by the algorithm are the ones with lower lifecycle impact and quicker return on investment. It can be observed that measures with lower environmental, energetic and economic performances are not selected to be part of any portfolio, as they have a negative impact on the overall objectives.

There are some measures which stand out as more interesting to be funded and supported by energy efficiency programs. Between the constructive measures, the application of XPS to façade walls in multi-dwelling buildings with gas heating and electric cooling, in any of the eras considered, reveals itself as the measure with a better performance accordingly to the portfolio objectives, considering its impact on the portfolio budget. In terms of technologic measures, although not being the measure that represent the highest lifetime energy savings, in the context of energy efficiency portfolios, the replacement of CFL lamps with LED lamps is given as the most interesting measure to be funded. The fact that this technology has low lifecycle impacts and low impact in the portfolio budget leads to its large-scale inclusion in most portfolios. These measures represent the ones most included in different portfolios, as well as the ones highest number of implementations in each portfolio, leading to more budget allocated to them.

Another data given by the solutions presented that is important to analyse is the number of implementations of different measures for portfolios with different sizes. It is possible to see that measures with lower impact on the overall budget are preferably chosen to take part in smaller portfolios than other measures with similar strong return indicators, both economic and environmental, but with higher individual impact on the portfolio. These results in constructive measures having less budget allocated in smaller portfolios, while increasing the budget allocated to technological measures, specifically to the replacement of CFL's with LED's. This measure approximately doubles its number of implementations from portfolios with 20 measures to portfolios with only 10 measures, while other measures with a high number of implementations in larger portfolios see that number reduce drastically in smaller portfolios. This decrease can be observed, for example, for measure 41, the installation of 35mm XPS to façade walls of buildings built in or after the year of

2013. Although the tendency amongst the constructive measures is the decrease of number of implementations towards smaller portfolios, there are some exceptions where the budget allocated to those measures see its value increased. For example, measures 3, 28, 31 and 33 have a considerably higher number of implementations in a portfolio with 10 measures than in the other type of portfolio.

As expected, measures with low economic and environmental return rates and with higher impact on the overall budget were excluded from most of the portfolios given by the optimization algorithm, or even excluded from all the portfolios. For example, measures related to EPS insulation or the installation of PVC double-glaze windows are less chosen to be supported when compared to other measures, as their impact on the overall budget is too high for the energy savings they represent.

6.1. LCA approach vs Traditional approach

In this section, it is analysed the differences between the measures selected to take part of the energy efficiency portfolios when considering the entire lifecycle of a measure and when using a more traditional approach, considering only the use-phase impacts. In order to compare these two strategies, a simulation was also made considering the objectives used in the measure evaluation in existing programs. In this case, we have selected as objectives for the algorithm the maximization of the SIR and the minimization of the PBT, while constraining each portfolio to the same budget as considered before. The parametrization of the algorithm is the same as the one used to form energy efficiency measures using an LCA approach. The results given by the algorithm for a traditional approach are detailed in Table A.8 to Table A.11, and the number of implementations of each measure in each portfolio is visually represented in Figure 6.4.

When looking into the differences between the portfolios considering a lifecycle approach and the ones only considering the use-phase, it is possible to observe that in the last case there is less diversity in terms of the measures selected to be funded.

As expected, there are some similarities in terms of the measures selected since some of these measures have a lifecycle impact that doesn’t overcome the savings obtained during the operational phase of the portfolios. Particularly, measures 17, 29 and 33 reveal a strong presence in the resulting portfolios both using a lifecycle approach and a traditional approach.

However, there are some relevant differences that are important to consider, and that justify the importance of selecting measures based on their lifecycle impacts and performance. With a traditional approach there is less diversity of measures selected for the portfolios, and this translates in a lower selection of measures that have a better impact in the lifecycle performance of the portfolios, even though their use-phase savings might not be as high as other measures. This can be seen in the reduction of measures related to the refurbishment of insulation and windows in older buildings (before 1960 until 1990), as well as in measures 41 and 45. This last example, measure 45, which consists in the substitution of CFL's with LED's is a measure that has a high lifecycle performance, and is therefore one of the most selected measures to be part of energy efficiency portfolios that follow a lifecycle approach. However, when compared to other measures, its energy and carbon savings obtained during the operation phase do not represent such a big impact, and therefore it was not considered by the algorithm to be included in any portfolio. This can be seen as an example for why it is urgent to select energy efficiency measures to be funded and implemented considering their LCA, if an energy policy supporting environmental objectives is to be followed.

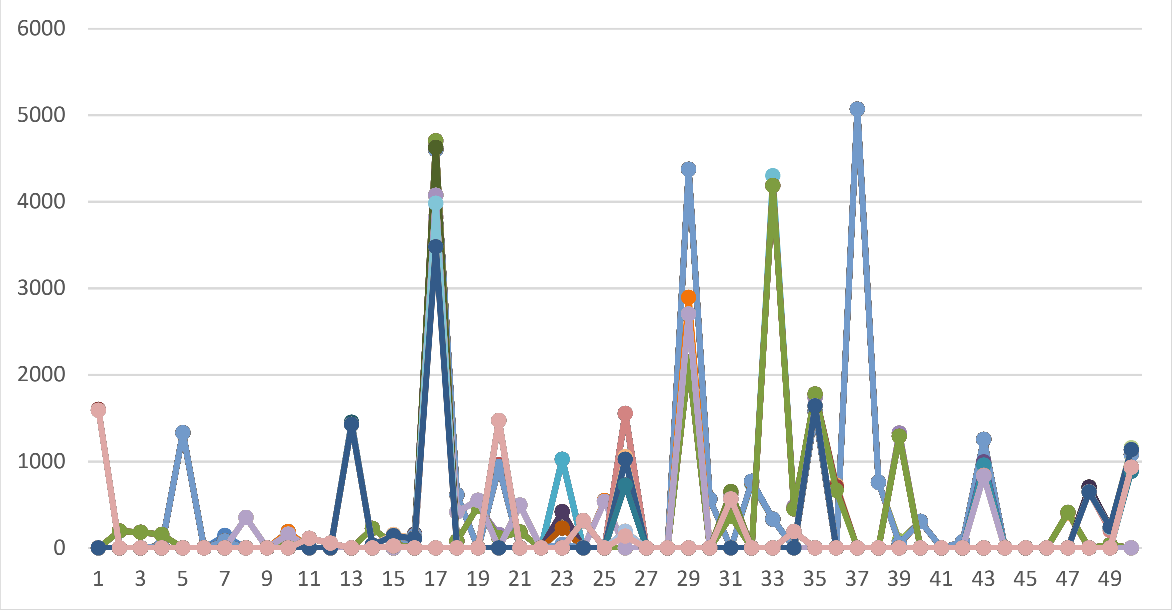

Figure 6.4 - Number of implementations of each measure (1 to 50) in each portfolio using a traditional approach.

6.2. Portfolio impact on different strategies

To analyse the impact of a portfolio on different objectives and strategies adopted by decision-makers, it is necessary to investigate the performance of each portfolio on the different selected objectives. Figure 6.5 and Figure 6.6 show the level of risk taken by choosing energy efficiency portfolio with different levels of return and energy payback. The numeric values for these objectives are detailed in Table A.7. For this analysis, only the non-dominated solutions were considered, as they have already been selected as the best options between all the solution population.

Observing Figure 6.5, it is possible to see that a portfolio with a higher number of measures have a higher return on investment. However, the risk associated to the choice of these portfolios is higher, as well as its EPBT, as shown in Figure 6.6. This indicates that more aggressive strategies, related to the choice of higher risk portfolios, leads to higher variety of measures to be implemented, while more conservative strategies lead to the selection of portfolios with less measures.

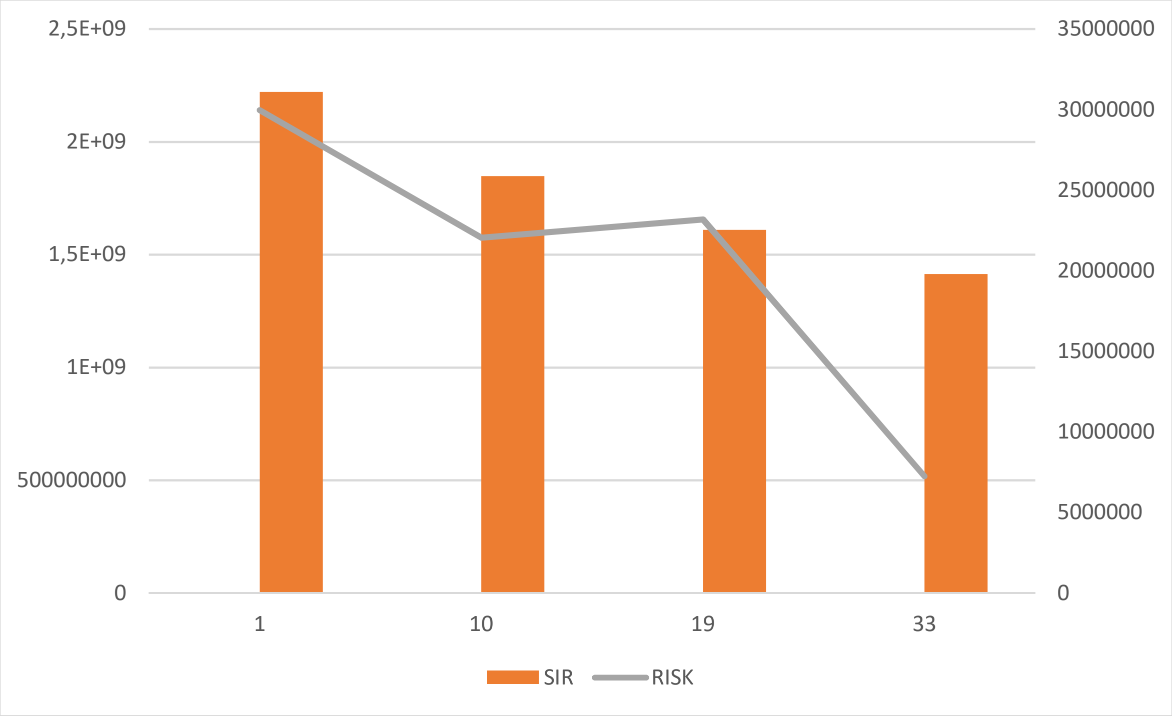

Figure 6.5 - Portfolio return vs Risk

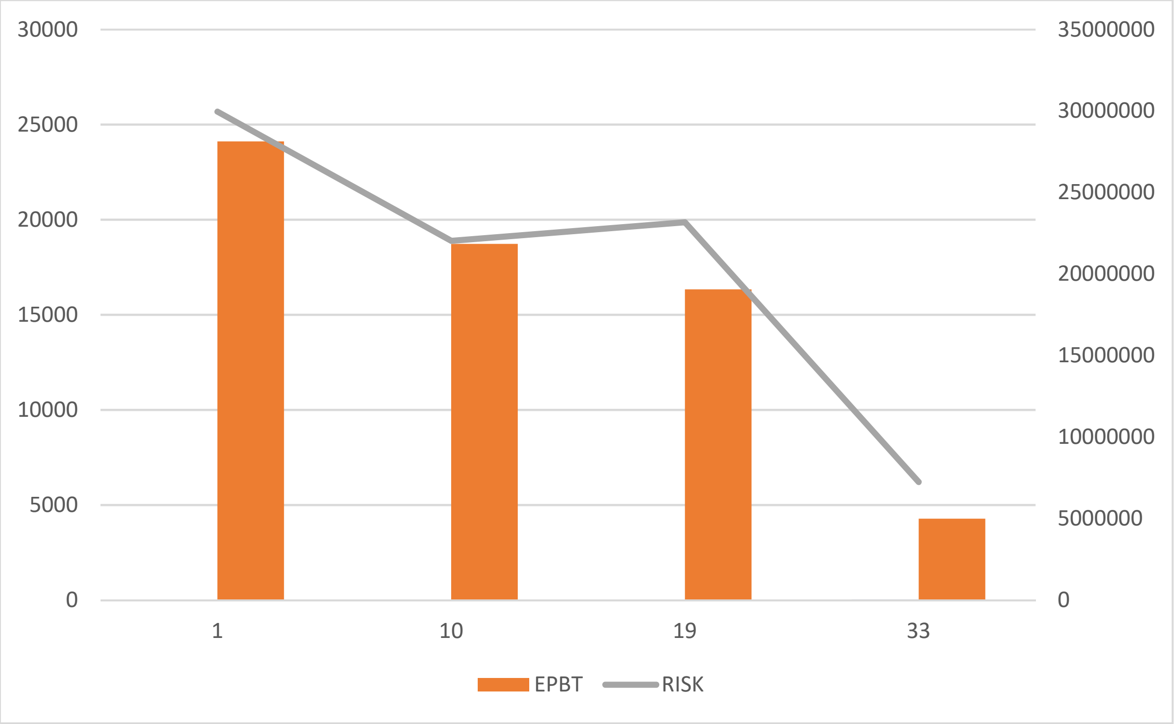

Figure 6.6 - Portfolio EPBT vs Risk

Higher risk portfolios allocate more investment to constructive measures and to the substitution of heating systems by heat pumps, while smaller and more conservative portfolios tend to allocate more budget to the substitution of CFL's with LED's. This can be justified by the high energy performance and return of this measure, as well as the other measures selected to be part of more conservative portfolios.

For not too aggressive nor too conservative strategies, with the selection of portfolios with 20 measures, there are several options to be considered. Moving on into the direction of less risk involved in the portfolio, the amount of investment allocated to technological measures grows, eliminating or reducing the investment in lower performance constructive measures.

It is possible to conclude that portfolios with 10 measures to be implemented are the ones that present a better trade-off between risk and return, showing better portfolio energetic and environmental performance, with a reasonable economic return rate.

7. CONCLUSION

The main objective of this work was to create a framework which could help decision-makers allocate investment in energy efficiency measures portfolios, considering a lifecycle approach.

This objective was fulfilled by designing a multi-objective model, and using the NSGA-II, to create and evaluate portfolios of energy efficiency measures, evaluated according to three different objectives: return, liquidity and a risk. The SIR (to be maximized) was considered as a proxy of return, whereas the EPBT (to be minimized) was selected as a liquidity measure. Finally, the maximization of the minimum difference between the energy savings and the embodied energy of each portfolio, evaluated the risk of investing in a portfolio on which the embodied energy exceed the energy savings. These objectives explicitly consider the entire energy and environmental lifecycle performance of each measure under scrutiny. This specific feature differentiates this approach from the commonly used methods that evaluate energy efficiency measures.

Based on a characterization of the Portuguese residential stock in terms of the construction necessities, as well as energy performance, and on measures supported by previous energy efficiency programs, 50 measures were selected to be evaluated by the framework to be developed. These measures were then characterized according to their energy and environmental lifecycle performance, and then evaluated according to different indicators, which included the ones selected as objectives.

After an initial phase of familiarizing with the NSGA-II, it was possible to start to parametrize the algorithm in terms of the mutation and crossover indexes. This parametrization was made by trial and error, analysing the results and modifying the indexes until reaching the most desirable results.

With the correct parametrization, it was possible to run the algorithm to 500 generations and investigate the constitution of the final solution portfolios and their performance on the selected objectives. The optimization algorithm was also run with more traditional objectives, focused only on the use-phase impacts of the measures, in order to compare both approaches.

Based on the results given by each simulation, it was possible to conclude that there are significant changes to the portfolios considering a lifecycle approach when compared to the ones considering only the use-phase impacts. Some measures that have a positive impact and improve the portfolio performance on use-phase objectives, therefore selected to be part of the funded measures, did not have such a strong presence in portfolios that evaluate these measures in all their lifecycle. This shows that, with the improvement of the equipment efficiency in terms of its use-phase, it is necessary to start considering the production and disposal phases of that equipment when selecting measures to be funded.

Another conclusion possible to draw from the results was that following more aggressive strategies, with higher risk, show a higher diversity of measures selected, while more conservative strategies result in portfolios with less measures.

7.1. Future Work

As future work in this field, it would be interesting to widen the scope of this analysis to other sectors rather than the residential sector, in order to form portfolios with efficiency measures.

Another development to the work made so far would be using different objective combinations, to observe the differences in the solutions presented.

It would also be important to further develop the methods and algorithms used to create the energy efficiency portfolios, in order to obtain the best solutions possible.

REFERENCES

[1] “Greenhouse Gas Emissions | Relatório do Estado do Ambiente.” [Online]. Available: https://rea.apambiente.pt/content/greenhouse-gas-emissions?language=en. [Accessed: 13-Nov-2019].

[2] “PORDATA - Ambiente de Consulta.” [Online]. Available: https://www.pordata.pt/DB/Portugal/Ambiente+de+Consulta/Tabela. [Accessed: 28-Jan-2020].

[3] D. 2002/91/EC, “DIRECTIVE 2002/91/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2002 on the energy performance of buildings,” pp. 65–71, 2003.

[4] P. Europeu, P. Europeu, J. Oficial, J. Oficial, P. Europeu, and J. Oficial, “Directiva 2010/31/UE do Parlamento Europeu e do Conselho, de 19 de Maio de 2010 , relativa ao desempenho energético dos edifícios,” *J. Of. nº L 153*, pp. 13–35, 2010.

[5] “National action plans and annual progress reports | Energy.” [Online]. Available: https://ec.europa.eu/energy/en/topics/energy-efficiency/targets-directive-and-rules/national-energy-efficiency-action-plans. [Accessed: 25-Jan-2020].

[6] “PNAEE.” [Online]. Available: http://www.pnaee.pt/pnaee#enquadramentopnaee. [Accessed: 26-Jan-2020].

[7] W.-N. Lee, H.-J. Kim, J.-B. Park, J.-H. Roh, and M.-S. Chae, “Development of Investment Strategies of Energy Efficiency Programs in Korea,” *J. Int. Counc. Electr. Eng.*, vol. 3, no. 1, pp. 38–44, 2013.

[8] G. P. Trachanas, A. Forouli, N. Gkonis, and H. Doukas, “Hedging uncertainty in energy efficiency strategies: a minimax regret analysis,” *Oper. Res.*, pp. 1–16, 2018.

[9] A. Forouli, H. Doukas, A. Nikas, J. Sampedro, and D. J. Van de Ven, “Identifying optimal technological portfolios for European power generation towards climate change mitigation: A robust portfolio analysis approach,” *Util. Policy*, vol. 57, no. January, pp. 33–42, 2019.

[10] V. K. Singh, C. O. Henriques, and A. G. Martins, “A multiobjective optimization approach to support end-use energy efficiency policy design – The case-study of India,” *Int. J. Sustain. Energy Plan. Manag.*, vol. 23, no. October, pp. 55–68, 2019.

[11] I. INE, *Estatísticas da Construção e Habitação - 2018*. 2018.

[12] I. P. Instituto Nacional de Estatística, *Censos 2011 Resultados Definitivos - Portugal*. 2007.

[13] I. P. e D.-G. de E. e G. Instituto Nacional de Estatística, *Inquérito ao Consumo de*

Energia no Sector Doméstico. 2010.

[14] Diário da Républica, “Decreto-Lei n.º 118/2013, DE 20 DE agosto (desempenho energético dos edifícios),” *Diário da República*, vol. 159, pp. 4988–5005, 2013.

[15] “Estatísticas - Sistema de Certificação Energética dos Edifícios.” [Online]. Available: https://www.sce.pt/estatisticas/. [Accessed: 28-Nov-2019].

[16] “Estatísticas - Sistema de Certificação Energética dos Edifícios.” [Online]. Available: https://www.sce.pt/estatisticas/. [Accessed: 28-Jan-2020].

[17] A. Observatorio da Energia, DGEG, *Energia em números*. 2019.

[18] A. Pinto and R. Fragoso, “SOLAR PASSIVO DE HABITAÇÕES Estação de Aquecimento,” 2018.

[19] A. Shukla, R. Tiwari, and R. Kala, “Genetic programming,” *Stud. Comput. Intell.*, vol. 307, no. 1989, pp. 209–234, 2010.

[20] H. Ishibuchi, Y. Sakane, N. Tsukamoto, and Y. Nojima, “Evolutionary many-objective optimization by NSGA-II and MOEA/D with large populations,” *Conf. Proc. - IEEE Int. Conf. Syst. Man Cybern.*, vol. 1, pp. 1758–1763, 2009.

[21] E. G. Shopova and N. G. Vaklieva-Bancheva, “BASIC-A genetic algorithm for engineering problems solution,” *Comput. Chem. Eng.*, vol. 30, no. 8, pp. 1293–1309, Jun. 2006.

[22] A. Mitsos, B. Chachuat, and P. I. Barton, “Global optimization of algorithms,” *AIChE Annu. Meet. Conf. Proc.*, 2008.

[23] ERSE, “FICHAS DE AVALIAÇÃO DOS CRITÉRIOS MÉTRICOS PPEC 2017-2018,” 2018.

[24] T. Filipe *et al.*, “Avaliação de Medidas de Eficiência Energética em Edifícios Residenciais”, Coimbra, 2016.

[25] COELHO, Dulce Helena de Carvalho - Apoio à decisão em planeamento energético urbano integrado. Coimbra : [s.n.], 2013. Ph.D dissertation

[26] E. Polystyrene and F. Insulation, “with alternative flame retardant EXIBA - European Extruded Polystyrene Insulation Board Association,” 2019.

[27] D. Programme, P. Declaration, E. C. O. E. P. D. Ref, and E. E. Manufacturers, “Environmental product declaration,” 2017.

[28] Q. K. E and E. P. P. A, “Environmental Product Declaration for PVC-U plastic windows with the dimensions of 1.23 x 1.48 m and insolated double-glazing”, 2016.

[29] P. Principi and R. Fioretti, “A comparative life cycle assessment of luminaires for general lighting for the of fi ce e compact fl uorescent (CFL) vs Light Emitting Diode (LED) e a case study,” *J. Clean. Prod.*, vol. 83, pp. 96–107, 2014.

[30] “Life cycle analysis of an OSRAM halogen lamp – OSRAM Group Website.” [Online]. Available: https://www.osram-group.com/en/sustainability/environmental/product-lifecycle-management/lca-hal. [Accessed: 30-Oct-2019].

[31] “Life cycle analysis of an OSRAM light-emitting diode lamp – OSRAM Group Website.” [Online]. Available: https://www.osram-group.com/en/sustainability/environmental/product-lifecycle-management/lca-led. [Accessed: 30-Oct-2019].

[32] A. Hugo and R. Zmeureanu, “Residential solar-based seasonal thermal storage systems in cold climates: Building envelope and thermal storage,” *Energies*, vol. 5, no. 10, pp. 3972–3985, 2012.

[33] B. Greening and A. Azapagic, “Domestic heat pumps : Life cycle environmental impacts and potential implications for the UK,” *Energy*, vol. 39, no. 1, pp. 205–217, 2012.

[34] S. Longo, M. Cellura, F. Guarino, V. La Rocca, and G. Maniscalco, “Embodied energy and environmental impacts of a biomass boiler : a life cycle approach,” vol. 3, no. 2, pp. 214–226, 2015.

[35] P. Piroozfar, F. Pomponi, and E. R. P. Farr, “Life Cycle Assessment of Domestic Hot Water Systems : A Comparative Analysis,” vol. 44, no. 0, pp. 1–23, 2013.

[36] “APREN - Production.” [Online]. Available: https://www.apren.pt/en/renewable-energies/production. [Accessed: 17-Oct-2019].

[37] A. March, “Portuguese National Inventory Report on Greenhouse Gases , 1990 - 2017 Submitted Under the Artº 5 and 7 of Regulation (Eu) No . 525 / 2013 of the European Parliament and of the Council on the Greenhouse Gas Monitoring Mechanism (Mmr),” no. 525, pp. 1990–2017, 2019.

[38] “PORDATA - Recycling rate of municipal waste (%).” [Online]. Available: https://www.pordata.pt/en/Europe/Recycling+rate+of+municipal+waste+(percentage)-3426. [Accessed: 25-Nov-2019].

[39] ERSE, “Parâmetros do PPEC 2013-2014, no âmbito dos artigos 21.º e 22.º das Regras do PPEC,” *Erse*, pp. 1–4, 2013.

[40] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, “A fast and elitist multiobjective genetic algorithm: NSGA-II,” *IEEE Trans. Evol. Comput.*, vol. 6, no. 2, pp. 182–197, 2002.

[41] M. M. Hamdan, “The Distribution Index in Polynomial Mutation for Evolutionary Multiobjective Optimisation Algorithms: An Experimental Study,” *Proc. Int. Conf. Electron. Comput. Technol.*, 2012.

ANNEXES

MEASURE	TECHNOLOGY	INITIAL COST	CRADLE-TO-GATE EMISSIONS	REDUCTION IN USE PHASE EMISSIONS	END-OF-LIFE EMISSIONS	USE PHASE ENERGY SAVINGS	LIFETIME	RECYCLING RATE
		(€)	(kgCO2eq)	(kgCO2eq/year)	(kgCO2eq)	(GJ/year)	(years)	(%)
1	XPS 35mm	461.67	272.95	1331.08	91.06	47.49	35.00	0.28
2	EPS 110mm	3229.145	5660.71	1331.08	806.10	47.49	35.00	0.28
3	XPS 35mm	437.055	258.40	524.04	86.21	18.70	35.00	0.28
4	PVC frame double-gazed window	1134	783.12	56.35	-45.16	1.87	40.00	0.28
5	XPS 35mm	509.805	301.41	269.90	100.56	9.63	35.00	0.28
6	EPS 110mm	3565.83	6250.92	269.90	890.15	9.63	35.00	0.28
7	XPS 35mm	547	323.40	655.87	107.89	23.40	35.00	0.28
8	PVC frame double-gazed window	1417.5	978.90	76.43	-56.45	2.73	40.00	0.28
9	XPS 35mm	435.41	257.43	230.51	85.88	8.22	35.00	0.28
10	EPS 110mm	3045.495	5338.77	230.51	760.25	8.22	35.00	0.28
11	XPS 35mm	423.38	250.31	507.64	83.51	18.11	35.00	0.28
12	PVC frame double-gazed window	2929.5	2023.06	157.96	-116.65	5.64	40.00	0.28
13	XPS 35mm	446.35	263.89	236.31	88.04	8.43	35.00	0.28

14	EPS 110mm	3122.015	5472.91	236.31	779.36	8.43	35.00	0.28
15	XPS 35mm	2922.73	266.48	540.43	88.90	19.28	35.00	0.28
16	PVC frame double-gazed window	3118.5	2153.58	168.15	-124.18	6.00	40.00	0.28
17	XPS 35mm	125.81	74.38	362.74	24.82	12.94	35.00	0.28
18	EPS 110mm	879.98	1542.61	362.74	219.67	12.94	35.00	0.28
19	PVC frame double-gazed window	931.77	643.46	43.08	-37.10	1.54	40.00	0.28
20	XPS 35mm	130.185	76.97	68.92	25.68	2.46	35.00	0.28
21	EPS 110mm	910.59	1596.27	68.92	227.31	2.46	35.00	0.28
22	PVC frame double-gazed window	967.68	668.26	52.18	-38.53	1.86	40.00	0.28
23	XPS 35mm	141.125	83.44	74.71	27.84	2.67	35.00	0.28
24	EPS 110mm	987.11	1730.41	74.71	246.41	2.67	35.00	0.28
25	PVC frame double-gazed window	1315.44	908.42	70.93	52.38	2.53	40.00	0.28
26	XPS 35mm	137.845	81.50	72.98	27.19	2.60	35.00	0.28
27	EPS 110mm	964.15	1690.16	72.98	240.68	2.60	35.00	0.28
28	PVC frame double-gazed window	1581.93	1092.45	85.30	-62.99	3.04	40.00	0.28
29	XPS 35mm	125.81	74.38	362.74	24.82	12.94	35.00	0.28
30	EPS 110mm	879.98	1542.61	362.74	219.67	12.94	35.00	0.28
31	XPS 35mm	355.55	210.21	426.31	70.13	15.21	35.00	0.28
32	PVC frame double-gazed window	931.77	643.46	43.08	-37.10	1.54	40.00	0.28

33	XPS 35mm	130.185	76.97	68.92	25.68	2.46	35.00	0.28
34	EPS 110mm	910.59	1429.67	68.92	227.31	2.46	35.00	0.28
35	XPS 35mm	382.9	226.38	459.11	75.52	16.38	35.00	0.28
36	PVC frame double-gazed window	967.68	668.37	50.24	-38.53	1.79	40.00	0.28
37	XPS 35mm	141.125	83.44	74.71	27.84	2.67	35.00	0.28
38	EPS 110mm	987.11	1549.81	74.71	246.41	2.67	35.00	0.28
39	XPS 35mm	519.65	307.23	623.07	102.50	22.23	35.00	0.28
40	PVC frame double-gazed window	1315.44	908.42	70.93	-52.38	2.53	40.00	0.28
41	XPS 35mm	137.845	81.50	72.98	27.19	2.60	35.00	0.28
42	EPS 110mm	964.15	1690.16	72.98	240.68	2.60	35.00	0.28
43	XPS 35mm	574.35	339.57	688.66	113.29	24.57	35.00	0.28
44	PVC frame double-gazed window	1581.93	1092.45	65.12	-62.99	2.32	40.00	0.28
45	LED	19.99	0.13	26.89	0.00	0.31	25.00	0.44
46	LED	3.25	2.40	6.96	0.00	0.08	25.00	0.44
47	Solar Heater with Electric Backup	499.5	308.83	288.80	0.00	3.29	20.00	0.44
48	Heat Pump	1058	1293.75	-1652.31	0.00	18.90	20.00	0.44
49	Biomass Boiler	2570	160.32	2.73	0.00	10.51	15.00	0.44
50	Heat Pump	595.8	1293.75	615.40	0.00	7.00	20.00	0.44

Table A.1 - LCA and characterization of the measures

MEASURE	PBT	EPTB (LOCAL)	EPBT (GLOBAL)	CPBT	SIR	ES	EE
1	0.19	0.01	0.09	0.27	64.67	461709.50	1150.15
2	1.31	0.05	1.55	4.86	9.25	461709.50	20432.90
3	0.45	0.01	0.21	0.66	26.89	181772.50	1088.83
4	11.68	-0.08	4.49	13.10	1.04	20784.00	2331.71
5	1.02	0.03	0.47	1.49	11.87	93619.40	1270.07
6	7.14	0.30	8.44	26.46	1.70	93619.40	22563.33
7	0.45	0.01	0.21	0.66	26.89	227500.00	1362.73
8	10.02	-0.07	3.85	12.07	1.21	30300.00	2914.64
9	1.02	0.03	0.47	1.49	11.88	79958.20	1084.73
10	7.14	0.30	8.44	26.46	1.70	79958.20	19270.83
11	0.45	0.01	0.21	0.66	26.89	176085.00	1054.76
12	10.02	-0.07	3.85	12.07	1.21	62620.00	6023.59
13	1.02	0.03	0.47	1.49	11.88	81967.20	1111.99
14	7.14	0.30	8.44	26.46	1.70	81967.20	19755.02
15	2.92	0.01	0.21	0.66	4.15	187460.00	1122.89
16	10.02	-0.07	3.85	12.07	1.21	66660.00	6412.21
17	0.19	0.01	0.09	0.27	64.67	125821.50	313.43
18	1.31	0.05	1.55	4.86	9.25	125821.50	5568.20
19	11.68	-0.08	4.49	14.08	1.04	17077.52	1915.89
20	1.02	0.03	0.47	1.49	11.88	23907.10	324.33
21	7.14	0.30	8.44	26.46	1.70	23907.10	5761.89
22	10.02	-0.07	3.85	12.07	1.21	20684.80	1989.73
23	1.02	0.03	0.47	1.49	11.88	25916.10	351.59
24	7.14	0.30	8.44	26.46	1.70	25916.10	6246.08
25	10.02	0.07	4.32	13.55	1.21	28118.40	3035.80
26	1.02	0.03	0.47	1.49	11.87	25313.40	343.41
27	7.14	0.30	8.44	26.46	1.70	25313.40	6100.81
28	10.02	-0.07	3.85	12.07	1.21	33814.80	3252.73
29	0.19	0.01	0.09	0.27	64.67	125821.50	313.43
30	1.31	0.05	1.55	4.86	9.25	125821.50	5568.20
31	0.45	0.01	0.21	0.66	26.89	147875.00	885.78
32	11.68	-0.08	4.49	14.08	1.04	17077.52	1915.89
33	1.02	0.03	0.47	1.49	11.88	23907.10	324.33
34	7.14	0.30	7.66	24.04	1.70	23907.10	5235.49
35	0.45	0.01	0.21	0.66	26.89	159250.00	953.91
36	10.40	-0.07	4.00	12.54	1.16	19917.20	1990.05
37	1.02	0.03	0.47	1.49	11.88	25916.10	351.59
38	7.14	0.30	7.66	24.04	1.70	25916.10	5675.45
39	0.45	0.01	0.21	0.66	26.89	216125.00	1294.60
40	10.02	-0.07	3.85	12.07	1.21	28118.40	2704.79

41	1.02	0.03	0.47	1.49	11.87	25313.40	343.41
42	7.14	0.30	8.44	26.46	1.70	25313.40	6100.81
43	0.45	0.01	0.21	0.66	26.89	238875.00	1430.87
44	13.12	-0.09	5.04	15.81	0.92	25814.80	3252.73
45	1.26	0.00	0.00	0.00	15.34	2124.31	0.42
46	0.79	0.00	0.34	0.34	24.36	550.00	7.58
47	2.93	0.00	1.07	1.07	2.74	18250.00	975.80
48	1.08	0.00	0.78	-0.78	3.72	105000.00	4087.81
49	4.71	0.00	0.17	58.66	1.34	43800.00	506.56
50	1.64	0.00	2.10	2.10	4.89	38888.89	4087.81

Table A.2 - Performance of the measures according to the selected indicators

PORTFOLIO	**SIZE**	**MEASURE**														
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1	30	0	25	1138	0	845	0	1133	0	316	123	0	0	1097	0	36
2	30	0	25	1138	0	845	0	1133	0	316	123	0	0	1097	0	36
3	30	0	25	1138	0	845	0	1133	0	316	123	0	0	1097	0	36
4	30	0	25	1138	0	845	0	1133	0	316	123	0	0	1097	0	36
5	30	0	25	922	0	845	0	1133	0	316	123	0	0	1097	0	36
6	30	0	25	922	0	845	0	1133	0	316	123	0	0	1097	0	36
7	30	0	25	922	0	844	0	1133	0	316	123	0	0	1097	0	36
8	30	0	25	922	0	844	0	1133	0	316	123	0	0	1097	0	36
9	30	0	25	922	0	844	0	1133	0	316	123	0	0	1097	0	36
10	20	544	0	0	73	0	0	1081	0	903	0	958	0	0	0	10
11	20	544	0	0	73	0	0	1081	0	903	0	958	0	0	0	10
12	20	544	0	0	73	0	0	1081	0	903	0	958	0	0	0	10
13	20	544	0	0	73	0	0	1081	0	903	0	958	0	0	0	10
14	20	544	0	0	73	0	0	1081	0	903	0	958	0	0	0	10
15	20	438	0	0	25	0	0	1137	0	903	0	958	0	0	0	10
16	20	438	0	0	25	0	0	1081	0	903	0	958	0	0	0	10
17	20	438	0	0	25	0	0	1081	0	904	0	958	0	0	0	10
18	20	438	0	0	25	0	0	1081	0	903	0	958	0	0	0	10
19	20	1431	0	0	0	989	0	0	232	0	0	1068	190	0	0	0
20	20	1431	0	0	0	989	0	0	232	0	0	1068	190	0	0	0
21	20	1431	0	0	0	989	0	0	232	0	0	1068	190	0	0	0
22	20	1431	0	0	0	989	0	0	232	0	0	1023	197	0	0	0
23	20	1431	0	0	0	989	0	0	232	0	0	1023	197	0	0	0
24	20	1431	0	0	0	989	0	0	232	0	0	1023	197	0	0	0
25	20	1431	0	0	0	989	0	0	232	0	0	1023	197	0	0	0
26	20	1431	0	0	0	989	0	0	232	0	0	1023	197	0	0	0
27	20	1431	0	0	0	989	0	0	232	0	0	1023	197	0	0	0

28	20	1431	0	0	0	989	0	0	232	0	0	1023	197	0	0	0
29	20	1431	0	0	0	989	0	0	232	0	0	1023	197	0	0	0
30	20	1431	0	0	0	989	0	0	232	0	0	1023	197	0	0	0
31	20	1431	0	0	0	989	0	0	232	0	0	1023	197	0	0	0
32	10	0	0	1076	0	0	0	0	0	0	0	0	0	0	0	81
33	10	0	0	1076	0	0	0	0	0	0	0	0	0	0	0	81
34	10	0	0	1076	0	0	0	0	0	0	0	0	0	0	0	81
35	10	0	0	1076	0	0	0	0	0	0	0	0	0	0	0	81
36	10	0	0	1076	0	0	0	0	0	0	0	0	0	0	0	81
37	10	0	0	1076	0	0	0	0	0	0	0	0	0	0	0	81
38	10	0	0	1076	0	0	0	0	0	0	0	0	0	0	0	81
39	10	0	0	1076	0	0	0	0	0	0	0	0	0	0	0	81
40	10	0	0	1103	0	0	0	0	0	0	0	0	0	0	0	81
41	10	0	0	1076	0	0	0	0	0	0	0	0	0	0	0	81
42	10	0	0	1076	0	0	0	0	0	0	0	0	0	0	0	81
43	10	0	0	1157	0	0	0	0	0	0	0	0	0	0	0	81
44	10	0	0	1076	0	0	0	0	0	0	0	0	0	0	0	81
45	10	0	0	1076	0	0	0	0	0	0	0	0	0	0	0	81
46	10	0	0	881	0	0	0	0	0	0	0	0	0	0	0	81
47	10	0	0	881	0	0	0	0	0	0	0	0	0	0	0	70
48	10	0	0	881	0	0	0	0	0	0	0	0	0	0	0	33
49	10	0	0	781	0	0	0	0	0	0	0	0	0	0	0	81
50	10	0	0	781	0	0	0	0	0	0	0	0	0	0	0	81

Table A.3 - Energy efficiency portfolios with a lifecycle approach (Measures 1 to 15)

PORTFOLIO	SIZE	MEASURE														
		16	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
1	30	30	0	45	0	5132	64	0	1261	0	0	2243	0	0	4743	359
2	30	30	0	45	0	4253	64	0	1261	0	0	2243	0	0	4743	359
3	30	30	0	45	0	4253	64	0	1261	0	0	2243	0	0	4743	359
4	30	30	0	45	0	4253	64	0	1261	0	0	1789	0	0	4743	359
5	30	30	0	33	0	4253	64	0	1261	0	0	2243	0	0	4743	359
6	30	30	0	33	0	4253	64	0	1261	0	0	2243	0	0	4743	359
7	30	30	0	45	0	4253	62	0	1261	0	0	1973	0	0	4743	344
8	30	30	0	45	0	4253	62	0	1261	0	0	1973	0	0	4743	344
9	30	30	0	45	0	4253	62	0	1261	0	0	1912	0	0	4743	344
10	20	236	5669	253	0	0	38	0	296	0	0	0	0	0	0	478
11	20	236	5669	253	0	0	38	0	296	0	0	0	0	0	0	478
12	20	234	5669	253	0	0	38	0	296	0	0	0	0	0	0	478
13	20	234	5669	253	0	0	38	0	296	0	0	0	0	0	0	478
14	20	234	5669	253	0	0	38	0	296	0	0	0	0	0	0	478
15	20	234	5669	253	0	0	38	0	296	0	0	0	0	0	0	478
16	20	234	5669	253	0	0	38	0	296	0	0	0	0	0	0	478
17	20	234	5669	253	0	0	38	0	296	0	0	0	0	0	0	478
18	20	234	5669	253	0	0	31	0	296	0	0	0	0	0	0	478
19	20	221	0	753	0	141	438	0	0	0	0	0	0	0	0	426
20	20	221	0	753	0	141	438	0	0	0	0	0	0	0	0	426
21	20	221	0	753	0	141	438	0	0	0	0	0	0	0	0	426
22	20	221	0	528	0	141	438	0	0	0	0	0	0	0	0	426
23	20	221	0	528	0	141	438	0	0	0	0	0	0	0	0	426
24	20	221	0	528	0	141	438	0	0	0	0	0	0	0	0	426
25	20	221	0	528	0	141	438	0	0	0	0	0	0	0	0	426
26	20	221	0	528	0	141	438	0	0	0	0	0	0	0	0	426
27	20	221	0	528	0	141	438	0	0	0	0	0	0	0	0	506

28	20	221	0	528	0	141	438	0	0	0	0	0	0	0	0	426
29	20	221	0	528	0	141	438	0	0	0	0	0	0	0	0	426
30	20	221	0	528	0	141	438	0	0	0	0	0	0	0	0	426
31	20	221	0	528	0	141	438	0	0	0	0	0	0	0	0	320
32	10	0	3590	0	0	0	0	0	0	0	0	0	0	382	2909	0
33	10	0	3590	0	0	0	0	0	0	0	0	0	0	371	2909	0
34	10	0	3590	0	0	0	0	0	0	0	0	0	0	371	2959	0
35	10	0	3590	0	0	0	0	0	0	0	0	0	0	371	2832	0
36	10	0	3590	0	0	0	0	0	0	0	0	0	0	371	2667	0
37	10	0	3590	0	0	0	0	0	0	0	0	0	0	371	2667	0
38	10	0	3070	0	0	0	0	0	0	0	0	0	0	371	2667	0
39	10	0	3070	0	0	0	0	0	0	0	0	0	0	371	2667	0
40	10	0	2935	0	0	0	0	0	0	0	0	0	0	371	2667	0
41	10	0	2935	0	0	0	0	0	0	0	0	0	0	371	2667	0
42	10	0	2935	0	0	0	0	0	0	0	0	0	0	371	2667	0
43	10	0	2935	0	0	0	0	0	0	0	0	0	0	371	2667	0
44	10	0	2935	0	0	0	0	0	0	0	0	0	0	371	2667	0
45	10	0	2935	0	0	0	0	0	0	0	0	0	0	371	2667	0
46	10	0	2935	0	0	0	0	0	0	0	0	0	0	371	2667	0
47	10	0	2935	0	0	0	0	0	0	0	0	0	0	371	2667	0
48	10	0	2935	0	0	0	0	0	0	0	0	0	0	371	2667	0
49	10	0	2935	0	0	0	0	0	0	0	0	0	0	371	2667	0
50	10	0	2935	0	0	0	0	0	0	0	0	0	0	368	2667	0

Table A.4 - Energy efficiency portfolios with a lifecycle approach (Measures 16 to 30)

PORTFOLIO	SIZE	MEASURE														
		31	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**
1	30	766	228	5261	0	851	695	3747	102	180	0	2628	240	0	766	228
2	30	766	134	5261	0	851	695	3747	102	180	0	2628	240	0	766	134
3	30	766	134	5261	0	851	695	3747	102	180	0	2628	240	0	766	134
4	30	766	134	5261	0	851	695	3747	102	180	0	2628	240	0	766	134
5	30	766	134	5261	0	851	634	3671	85	180	0	2628	240	0	766	134
6	30	766	134	5261	0	851	634	3671	85	180	0	2628	240	0	766	134
7	30	766	134	5261	0	851	695	3671	102	180	0	2628	172	0	766	134
8	30	766	134	5261	0	851	695	3671	102	180	0	2628	172	0	766	134
9	30	766	134	5261	0	851	695	3671	102	180	0	2628	172	0	766	134
10	20	0	599	1263	251	0	0	0	528	0	361	4462	192	366	0	599
11	20	0	599	1263	251	0	0	0	528	0	361	4462	192	366	0	599
12	20	0	599	1263	251	0	0	0	528	0	361	4313	192	366	0	599
13	20	0	599	1263	235	0	0	0	528	0	361	4462	192	327	0	599
14	20	0	599	1263	235	0	0	0	528	0	361	4462	192	327	0	599
15	20	0	527	1263	251	0	0	0	567	0	361	4462	192	327	0	527
16	20	0	527	1263	251	0	0	0	567	0	361	4462	192	327	0	527
17	20	0	527	1263	251	0	0	0	528	0	361	4462	192	327	0	527
18	20	0	527	1263	251	0	0	0	528	0	361	4462	192	327	0	527
19	20	0	260	0	0	17	460	0	0	0	0	3915	0	1296	0	260
20	20	0	260	0	0	17	460	0	0	0	0	3915	0	1296	0	260
21	20	0	257	0	0	17	460	0	0	0	0	3915	0	1296	0	257
22	20	0	260	0	0	23	460	0	0	0	0	4271	0	1296	0	260
23	20	0	260	0	0	23	460	0	0	0	0	3915	0	1296	0	260
24	20	0	260	0	0	23	460	0	0	0	0	3915	0	1296	0	260
25	20	0	260	0	0	12	460	0	0	0	0	3915	0	1296	0	260
26	20	0	260	0	0	12	460	0	0	0	0	3915	0	1296	0	260
27	20	0	260	0	0	23	460	0	0	0	0	3219	0	1296	0	260

28	20	0	260	0	0	23	460	0	0	0	0	3219	0	1296	0	260
29	20	0	260	0	0	23	460	0	0	0	0	3219	0	1296	0	260
30	20	0	260	0	0	23	460	0	0	0	0	3219	0	1296	0	260
31	20	0	260	0	0	23	460	0	0	0	0	3219	0	1296	0	260
32	10	1109	0	3351	0	599	0	0	0	0	0	0	0	0	1109	0
33	10	1109	0	3351	0	599	0	0	0	0	0	0	0	0	1109	0
34	10	964	0	3351	0	599	0	0	0	0	0	0	0	0	964	0
35	10	964	0	3351	0	599	0	0	0	0	0	0	0	0	964	0
36	10	964	0	3351	0	599	0	0	0	0	0	0	0	0	964	0
37	10	964	0	3351	0	599	0	0	0	0	0	0	0	0	964	0
38	10	1171	0	3351	0	599	0	0	0	0	0	0	0	0	1171	0
39	10	1171	0	3351	0	599	0	0	0	0	0	0	0	0	1171	0
40	10	1171	0	3351	0	599	0	0	0	0	0	0	0	0	1171	0
41	10	1171	0	3351	0	599	0	0	0	0	0	0	0	0	1171	0
42	10	1171	0	3351	0	570	0	0	0	0	0	0	0	0	1171	0
43	10	1171	0	3351	0	447	0	0	0	0	0	0	0	0	1171	0
44	10	1073	0	3351	0	599	0	0	0	0	0	0	0	0	1073	0
45	10	1171	0	3351	0	447	0	0	0	0	0	0	0	0	1171	0
46	10	1171	0	3351	0	599	0	0	0	0	0	0	0	0	1171	0
47	10	1171	0	3351	0	599	0	0	0	0	0	0	0	0	1171	0
48	10	1171	0	3351	0	599	0	0	0	0	0	0	0	0	1171	0
49	10	1171	0	3351	0	599	0	0	0	0	0	0	0	0	1171	0
50	10	1171	0	3351	0	590	0	0	0	0	0	0	0	0	1171	0

TableA.5 - Energy efficiency portfolios with a lifecycle approach (Measures 31 to 45)

PORTFOLIO	SIZE	MEASURE				
		46	**47**	**48**	**49**	**50**
1	30	0	0	183	211	773
2	30	0	0	183	211	773
3	30	0	0	183	211	773
4	30	0	0	183	211	773
5	30	0	0	183	211	773
6	30	0	0	183	211	773
7	30	0	0	183	211	773
8	30	0	0	183	211	773
9	30	0	0	183	211	773
10	20	0	0	0	0	0
11	20	0	0	0	0	0
12	20	0	0	0	0	0
13	20	0	0	0	0	0
14	20	0	0	0	0	0
15	20	0	0	0	0	0
16	20	0	0	0	0	0
17	20	0	0	0	0	0
18	20	0	0	0	0	0
19	20	0	1487	0	12	87
20	20	0	1487	0	12	87
21	20	0	1487	0	12	87
22	20	0	1487	0	8	87
23	20	0	1487	0	12	87
24	20	0	1487	0	12	87
25	20	0	1487	0	12	87
26	20	0	1487	0	12	87
27	20	0	1487	0	8	87

28	20	0	1487	0	8	101
29	20	0	1487	0	8	87
30	20	0	1487	0	8	87
31	20	0	1487	0	8	87
32	10	0	0	0	193	0
33	10	0	0	0	193	0
34	10	0	0	0	193	0
35	10	0	0	0	193	0
36	10	0	0	0	193	0
37	10	0	0	0	193	0
38	10	0	0	0	201	0
39	10	0	0	0	197	0
40	10	0	0	0	197	0
41	10	0	0	0	197	0
42	10	0	0	0	197	0
43	10	0	0	0	197	0
44	10	0	0	0	197	0
45	10	0	0	0	197	0
46	10	0	0	0	197	0
47	10	0	0	0	197	0
48	10	0	0	0	197	0
49	10	0	0	0	197	0
50	10	0	0	0	197	0

Table A.6 - Energy efficiency portfolios with a lifecycle approach (Measures 46 to 50)

MEASURE	SIR	EPBT	RISK
1	2220946333	24109.95	29969055.98
2	2198336224	23269.8	29503542.43
3	2198336224	23269.8	29503542.43
4	2186854520	23054.43	29347778.32
5	2154682062	22930.13	29042637.96
6	2154682062	22930.13	29042637.96
7	2147282713	22572.62	28717978.35
8	2147282713	22572.62	28717978.35
9	2145722286	22543.35	28696809.15
10	1847146722	18723.52	22052628.61
11	1847146722	18723.52	22052628.61
12	1843263397	18645.95	21989907.75
13	1837468745	18587.23	21903159.09
14	1837468745	18587.23	21903159.09
15	1800669551	18464.87	21906958.14
16	1788046273	18453.24	21831344.22
17	1787151131	18157.19	21613120.2
18	1786853672	18089.71	21566002.19
19	1609105101	16341.44	23188484.51
20	1609105101	16341.44	23188484.51
21	1609056770	16328.74	23183062.35
22	1583108238	16178.58	22052460.49
23	1574290710	16010.16	21932430.79
24	1574290710	16010.16	21932430.79
25	1572201461	15942.81	21879936.72
26	1572201461	15942.81	21879936.72
27	1566500701	15802.37	22135057.38
28	1557027656	15709.14	21749912.17
29	1556467644	15678.86	21691046.5
30	1556467644	15678.86	21691046.5
31	1543112157	15514.45	21100002.11
32	1414689392	4321.704	7288271.401
33	1414321777	4279.874	7252909.587
34	1399250006	4253.881	7140307.293
35	1383261605	4242.802	7100479.246
36	1362534810	4228.44	7048847.58
37	1362534810	4228.44	7048847.58
38	1328073807	4227.854	7073162.751
39	1327913644	4227.219	7071310.428
40	1315857072	4221.132	7058506.494
41	1310993740	4215.521	7029374.915
42	1306408030	4209.496	7001906.34
43	1301596596	4200.751	6973085.761
44	1294550435	4190.503	6941632.887

45	1286821766	4183.71	6884583.866
46	1273593667	4170.172	6816100.815
47	1271568290	4167.907	6803968.712
48	1264724903	4160.254	6762976.502
49	1255525161	4149.329	6707869.649
50	1253935378	4136.731	6689905.99

Table A.7 - Portfolio performance on the selected lifecycle objectives.

PORTFOLIO	SIZE	MEASURE														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	20	0	0	0	28	1331	0	145	0	0	0	0	0	0	0	0
2	20	0	0	0	28	1331	0	82	0	0	0	0	0	0	0	0
3	20	0	0	0	28	1331	0	68	0	0	0	0	0	0	0	0
4	20	0	0	0	28	1331	0	82	0	0	0	0	0	0	0	0
5	20	0	0	0	28	1331	0	82	0	0	0	0	0	0	0	0
6	20	0	0	0	28	1331	0	82	0	0	0	0	0	0	0	0
7	20	0	0	0	28	1331	0	82	0	0	0	0	0	0	0	0
8	20	0	0	0	28	1331	0	82	0	0	0	0	0	0	0	0
9	20	0	0	0	28	1331	0	82	0	0	0	0	0	0	0	0
10	20	0	0	0	28	1331	0	82	0	0	0	0	0	0	0	0
11	20	0	0	0	28	1331	0	82	0	0	0	0	0	0	0	0
12	20	0	0	0	28	1331	0	82	0	0	0	0	0	0	0	0
13	20	0	0	0	28	1331	0	82	0	0	0	0	0	0	0	0
14	20	0	195	183	153	0	0	0	0	0	75	0	0	0	227	45
15	20	0	195	183	153	0	0	0	0	0	75	0	0	0	227	45
16	20	0	195	183	153	0	0	0	0	0	66	0	0	0	227	46
17	20	0	192	183	155	0	0	0	0	0	66	0	0	0	227	45
18	20	0	195	183	155	0	0	0	0	0	66	0	0	0	227	45
19	20	0	195	183	155	0	0	0	0	0	66	0	0	0	227	45
20	20	0	195	183	155	0	0	0	0	0	66	0	0	0	227	45
21	20	0	195	183	155	0	0	0	0	0	66	0	0	0	227	45
22	10	0	0	0	0	0	0	0	352	0	189	0	0	0	0	0
23	10	0	0	0	0	0	0	0	352	0	189	0	0	0	0	0
24	10	0	0	0	0	0	0	0	352	0	189	0	0	0	0	0
25	10	0	0	0	0	0	0	0	352	0	161	0	0	0	0	0
26	10	0	0	0	0	0	0	0	352	0	161	0	0	0	0	0
27	10	0	0	0	0	0	0	0	352	0	161	0	0	0	0	0

28	10	0	0	0	0	0	0	0	352	0	161	0	0	0	0	0
29	10	0	0	0	0	0	0	0	0	0	0	0	0	1429	35	157
30	10	0	0	0	0	0	0	0	0	0	0	0	0	1429	35	157
31	10	0	0	0	0	0	0	0	0	0	0	0	0	1429	35	143
32	10	0	0	0	0	0	0	0	0	0	0	0	0	1429	35	143
33	10	0	0	0	0	0	0	0	0	0	0	0	0	1429	29	143
34	10	0	0	0	0	0	0	0	0	0	0	0	0	1429	35	143
35	10	0	0	0	0	0	0	0	0	0	0	0	0	1454	35	143
36	10	0	0	0	0	0	0	0	0	0	0	0	0	1429	35	137
37	10	0	0	0	0	0	0	0	0	0	0	0	0	1429	35	137
38	10	0	0	0	0	0	0	0	0	0	0	0	0	1429	35	137
39	10	0	0	0	0	0	0	0	0	0	0	0	0	1429	35	143
40	10	0	0	0	0	0	0	0	0	0	0	0	0	1429	35	143
41	10	0	0	0	0	0	0	0	0	0	0	0	0	1429	35	143
42	10	0	0	0	0	0	0	0	0	0	0	0	0	1429	35	143
43	10	0	0	0	0	0	0	0	0	0	0	0	0	1429	35	143
44	10	1600	0	0	0	0	0	0	0	0	0	112	55	0	0	24
45	10	1589	0	0	0	0	0	0	0	0	0	112	55	0	0	24
46	10	1589	0	0	0	0	0	0	0	0	0	112	55	0	0	24
47	10	1589	0	0	0	0	0	0	0	0	0	112	55	0	0	24
48	10	1589	0	0	0	0	0	0	0	0	0	112	55	0	0	24
49	10	1589	0	0	0	0	0	0	0	0	0	112	55	0	0	24
50	10	1589	0	0	0	0	0	0	0	0	0	112	55	0	0	24

Table A.8 - Energy efficiency portfolios with a traditional approach (Measures 1 to 15)

PORTFOLIO	SIZE	MEASURE														
		16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	20	144	4601	615	0	961	0	0	1026	0	0	0	0	0	4376	563
2	20	144	4601	615	0	961	0	0	1026	0	0	0	0	0	4376	563
3	20	144	4601	615	0	941	0	0	1026	0	0	0	0	0	4376	563
4	20	144	4601	615	0	941	0	0	1026	0	0	0	0	0	4376	563
5	20	144	4601	615	0	941	0	0	1026	0	0	0	0	0	4376	563
6	20	159	4601	615	0	941	0	0	419	0	0	0	0	0	4376	563
7	20	159	4601	615	0	941	0	0	419	0	0	0	0	0	4376	563
8	20	151	4601	615	0	941	0	0	419	0	0	0	0	0	4376	563
9	20	144	4601	615	0	941	0	0	419	0	0	0	0	0	4376	563
10	20	138	4601	615	0	941	0	0	419	0	0	0	0	0	4376	563
11	20	144	4601	615	0	941	0	0	230	0	0	0	0	0	4376	563
12	20	144	4601	615	0	941	0	0	230	0	0	0	0	0	4376	563
13	20	144	4601	615	0	941	0	0	40	0	0	0	0	0	4376	563
14	20	0	4705	78	480	157	184	0	0	0	0	0	0	0	2146	0
15	20	0	4705	78	480	157	184	0	0	0	0	0	0	0	2146	0
16	20	0	4705	78	480	157	184	0	0	0	0	0	0	0	2146	0
17	20	0	4705	78	480	118	184	0	0	0	0	0	0	0	2146	0
18	20	0	4705	78	480	118	184	0	0	0	0	0	0	0	2146	0
19	20	0	4705	78	480	118	184	0	0	0	0	0	0	0	2146	0
20	20	0	4705	78	480	118	184	0	0	0	0	0	0	0	2146	0
21	20	0	4705	78	480	118	184	0	0	0	0	0	0	0	2146	0
22	10	0	3819	415	550	0	497	0	0	0	549	0	0	0	2705	0
23	10	0	3819	415	550	0	497	0	0	0	549	0	0	0	2705	0
24	10	0	3819	415	550	0	497	0	0	0	549	0	0	0	2895	0
25	10	0	3979	415	550	0	497	0	0	0	538	0	0	0	2705	0
26	10	0	3819	415	550	0	497	0	0	0	538	0	0	0	2705	0
27	10	0	3819	415	550	0	497	0	0	0	538	0	0	0	2705	0

28	10	0	3819	415	550	0	497	0	0	0	538	0	0	0	2705	0
29	10	117	4624	0	0	0	0	0	0	0	0	1555	0	0	0	0
30	10	117	4624	0	0	0	0	0	0	0	0	1555	0	0	0	0
31	10	117	4624	0	0	0	0	0	0	0	0	1555	0	0	0	0
32	10	109	4624	0	0	0	0	0	0	0	0	1555	0	0	0	0
33	10	109	4624	0	0	0	0	0	0	0	0	1555	0	0	0	0
34	10	109	4075	0	0	0	0	0	0	0	0	1555	0	0	0	0
35	10	109	4075	0	0	0	0	0	0	0	0	1555	0	0	0	0
36	10	109	4075	0	0	0	0	0	0	0	0	1555	0	0	0	0
37	10	109	4075	0	0	0	0	0	0	0	0	1555	0	0	0	0
38	10	109	4075	0	0	0	0	0	0	0	0	1555	0	0	0	0
39	10	109	4075	0	0	0	0	0	0	0	0	1056	0	0	0	0
40	10	109	4075	0	0	0	0	0	0	0	0	1056	0	0	0	0
41	10	109	3984	0	0	0	0	0	0	0	0	1056	0	0	0	0
42	10	109	3480	0	0	0	0	0	0	0	0	1056	0	0	0	0
43	10	109	3480	0	0	0	0	0	0	0	0	1024	0	0	0	0
44	10	0	0	0	0	1471	0	0	0	314	0	726	0	0	0	0
45	10	0	0	0	0	1471	0	0	0	314	0	726	0	0	0	0
46	10	0	0	0	0	1471	0	0	0	314	0	726	0	0	0	0
47	10	0	0	0	0	1471	0	0	0	314	0	726	0	0	0	0
48	10	0	0	0	0	1471	0	0	0	314	0	194	0	0	0	0
49	10	0	0	0	0	1471	0	0	0	314	0	194	0	0	0	0
50	10	0	0	0	0	1471	0	0	0	314	0	139	0	0	0	0

Table A.9 - Energy efficiency portfolios with a traditional approach (Measures 16 to 31)

PORTFOLIO	SIZE	MEASURE														
		31	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**
1	20	0	768	332	0	1576	0	5070	758	83	308	0	70	1255	0	0
2	20	0	768	332	0	1576	0	5070	758	83	308	0	70	1255	0	0
3	20	0	768	332	0	1576	0	5070	758	83	308	0	70	1255	0	0
4	20	0	768	332	0	1576	0	5070	758	50	308	0	70	1255	0	0
5	20	0	739	332	0	1576	0	5070	758	50	308	0	70	1255	0	0
6	20	0	768	332	0	1576	0	5070	758	50	308	0	70	1255	0	0
7	20	0	768	332	0	1576	0	5070	758	50	308	0	70	1255	0	0
8	20	0	768	332	0	1576	0	5070	758	50	308	0	70	1255	0	0
9	20	0	768	332	0	1576	0	5070	758	50	308	0	70	1255	0	0
10	20	0	768	332	0	1576	0	5070	758	50	308	0	70	1255	0	0
11	20	0	768	332	0	1576	0	5070	758	50	308	0	70	1255	0	0
12	20	0	759	332	0	1576	0	5070	758	45	308	0	70	1255	0	0
13	20	0	768	332	0	1576	0	5070	758	50	308	0	70	1255	0	0
14	20	368	0	4187	474	1733	724	0	0	1328	0	0	0	0	0	0
15	20	368	0	4187	474	1733	724	0	0	1328	0	0	0	0	0	0
16	20	368	0	4187	474	1733	724	0	0	1328	0	0	0	0	0	0
17	20	368	0	4300	451	1778	724	0	0	1292	0	0	0	0	0	0
18	20	368	0	4187	451	1778	724	0	0	1292	0	0	0	0	0	0
19	20	368	0	4187	451	1778	706	0	0	1292	0	0	0	0	0	0
20	20	368	0	4187	451	1778	706	0	0	1292	0	0	0	0	0	0
21	20	368	0	4187	451	1778	665	0	0	1292	0	0	0	0	0	0
22	10	627	0	0	0	0	0	0	0	0	0	0	0	996	0	0
23	10	627	0	0	0	0	0	0	0	0	0	0	0	957	0	0
24	10	627	0	0	0	0	0	0	0	0	0	0	0	833	0	0
25	10	627	0	0	0	0	0	0	0	0	0	0	0	833	0	0
26	10	627	0	0	0	0	0	0	0	0	0	0	0	841	0	0
27	10	627	0	0	0	0	0	0	0	0	0	0	0	829	0	0

28	10	627	0	0	0	0	0	0	0	0	0	0	0	829	0	0
29	10	0	0	0	0	1641	0	0	0	0	0	0	0	0	0	0
30	10	0	0	0	0	1641	0	0	0	0	0	0	0	0	0	0
31	10	0	0	0	0	1641	0	0	0	0	0	0	0	0	0	0
32	10	0	0	0	0	1641	0	0	0	0	0	0	0	0	0	0
33	10	0	0	0	0	1636	0	0	0	0	0	0	0	0	0	0
34	10	0	0	0	0	1641	0	0	0	0	0	0	0	0	0	0
35	10	0	0	0	0	1641	0	0	0	0	0	0	0	0	0	0
36	10	0	0	0	0	1641	0	0	0	0	0	0	0	0	0	0
37	10	0	0	0	0	1641	0	0	0	0	0	0	0	0	0	0
38	10	0	0	0	0	1641	0	0	0	0	0	0	0	0	0	0
39	10	0	0	0	0	1641	0	0	0	0	0	0	0	0	0	0
40	10	0	0	0	0	1641	0	0	0	0	0	0	0	0	0	0
41	10	0	0	0	0	1641	0	0	0	0	0	0	0	0	0	0
42	10	0	0	0	0	1641	0	0	0	0	0	0	0	0	0	0
43	10	0	0	0	0	1641	0	0	0	0	0	0	0	0	0	0
44	10	653	0	0	189	0	0	0	0	0	0	0	0	0	0	0
45	10	653	0	0	189	0	0	0	0	0	0	0	0	0	0	0
46	10	565	0	0	189	0	0	0	0	0	0	0	0	0	0	0
47	10	565	0	0	189	0	0	0	0	0	0	0	0	0	0	0
48	10	565	0	0	189	0	0	0	0	0	0	0	0	0	0	0
49	10	565	0	0	189	0	0	0	0	0	0	0	0	0	0	0
50	10	565	0	0	189	0	0	0	0	0	0	0	0	0	0	0

Table A.10 - Energy efficiency portfolios with a traditional approach (Measures 31 to 45)

PORTFOLIO	SIZE	MEASURE				
		46	47	48	49	50
1	20	0	0	0	0	1079
2	20	0	0	0	0	1079
3	20	0	0	0	0	1079
4	20	0	0	0	0	1079
5	20	0	0	0	0	1079
6	20	0	0	0	0	1079
7	20	0	0	0	0	1079
8	20	0	0	0	0	1079
9	20	0	0	0	0	1079
10	20	0	0	0	0	1079
11	20	0	0	0	0	1079
12	20	0	0	0	0	1079
13	20	0	0	0	0	1079
14	20	0	401	0	37	0
15	20	0	401	0	37	0
16	20	0	401	0	37	0
17	20	0	401	0	37	0
18	20	0	401	0	37	0
19	20	0	411	0	37	0
20	20	0	411	0	37	0
21	20	0	411	0	37	0
22	10	0	0	0	0	0
23	10	0	0	0	0	0
24	10	0	0	0	0	0
25	10	0	0	0	0	0
26	10	0	0	0	0	0
27	10	0	0	0	0	0

28	10	0	0	0	0	0
29	10	0	0	705	237	1134
30	10	0	0	705	237	1134
31	10	0	0	705	237	1134
32	10	0	0	705	237	1134
33	10	0	0	705	230	1134
34	10	0	0	705	237	1134
35	10	0	0	649	237	1134
36	10	0	0	649	237	1134
37	10	0	0	649	220	1134
38	10	0	0	649	199	1134
39	10	0	0	649	237	1159
40	10	0	0	649	237	1134
41	10	0	0	649	237	1134
42	10	0	0	649	245	1134
43	10	0	0	649	245	1134
44	10	0	0	0	0	932
45	10	0	0	0	0	932
46	10	0	0	0	0	932
47	10	0	0	0	0	885
48	10	0	0	0	0	932
49	10	0	0	0	0	932
50	10	0	0	0	0	932

Table A.11 - Energy efficiency portfolios with a traditional approach (Measures 46 to 50)

	SINGLE-DWELLING BUILDING				**MULTI-DWELLING BUILDING**							
	4 façades + Roof				2 façades				2 façades + Roof			
	≤1960	1961-1990	1991-2012	≥2013	≤1960	1961-1990	1991-2012	≥2013	≤1960	1961-1990	1991-2012	≥2013
APPLY 35MM XPS WALL INSULATION	1	5	9	13	17	20	23	26	29	33	37	41
APPLY 110MM EPS WALL INSULATION	2	6	10	14	18	21	24	27	30	34	38	42
APPLY 35MM XPS ROOF INSULATION	3	7	11	15	X	X	X	X	31	35	39	43
REPLACE SINGLE-GALZE WINDOWS WITH DOUBLE-GLAZE WINDOWS	4	8	12	16	19	22	25	28	32	36	40	44

Table A.12 - Constructive measures indexing