José Pedro Albuquerque Leitão de Oliveira e Costa

DECISION MAKING TOOL TO SELECT ENERGY EFFICIENCY MEASURES THROUGH PORTFOLIO EVALUATION CONSIDERING MULTIPLE BENEFITS

Dissertation within the Integrated Master's Degree in Electrical and Computer Engineering, specialized in energy under the supervision of Professor Álvaro Filipe Peixoto Cardoso de Oliveira Gomes and Professor Carla Margarida Saraiva de Oliveira Henriques and presented to the Department of Electrical and Computer Engineering of the Faculty of Sciences and Technology of the University of Coimbra

October 2020

FACULTY OF SCIENCE AND TECHNOLOGY OF UNIVERSITY OF COIMBRA

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGENEERING

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Coimbra, October 2020

This work was partially supported by project grant UIDB/00308/2020 and by the European Regional Development Fund through the COMPETE 2020 Program, FCT— Portuguese Foundation for Science and Technology within project T4ENERTEC (POCI-01-0145-FEDER-029820), as well as by the Energy for Sustainability Initiative of the University of Coimbra.

Acknowledgments

Ao Professor Àlvaro Gomes e à Professora Carla Henriques por toda a disponibilidade para a orientação deste trabalho, e, mais importante que tudo, pelo motivação e tranquilidade transmitida quando algo não corria pelo melhor.

Ao meu pai, que apesar de ser extremamente chato e preocupado, sei que sem ele não estaria onde estou hoje.

A todos os meus amigos, uns que me foram acompanhando ao longo da minha vida académica e outros ao longo da minha vida. Pelas brincadeiras, apoio, confiança, companheirismo e de certa forma, carinho. São pilares importantíssimos na minha vida, e tenho que agradacer por olharem por mim nos bons e maus momentos.

Um especial obrigado ao Filipe e ao Chico pela ajuda e disponibilidade para o esclarecimento de dúvidas e apoio durante a realização desta dissertação.

Ao próprio DEEC e a todos os elementos que o constituem, sem dúvida que me senti numa segunda casa. Vou ter saudades.

À minha namorada, que merece o agradecimento mais pomposo, por zelar pela minha sanidade mental em todo este processo e por ter sido uma das principais responsáveis por tudo de bom que me aconteceu neste presente ano. Por mais irregular e estranho que este 2020 esteja a ser, sem dúvida que foste uma dádiva. Mal posso esperar para o que ainda está para vir!

A todos, o meu especial e mais sincero Obrigado!

Abstract

It has been broadly acknowledged that the adoption of energy efficient measures is extremely important for reducing energy consumption and greenhouse gas emissions, also lowering the energy bill, and increasing energy supply security. Besides, the investment in energy efficient measures also entails other relevant benefits that are often overlooked.

In this context, the present work tries to develop a holistic approach by explicitly considering distinct multiple benefits associated with several energy efficient measures. In this framework, a multi-objective model has been built, which allows obtaining efficient solutions that contemplate portfolios of energy efficient measures applied to the Portuguese residential sector. This model considers five objective functions: the maximization of the savings to investment ratio (SIR), the minimization of the carbon payback time (CPBT), the minimization of the cost of conserved energy (CCE), the minimization of risk calculated through the use of different experts' points of view and the minimization of the deviation from the available budget. The solutions to the model are then computed through an adjusted implementation based on the Non-Dominated Sorting Genetic Algorithm. Finally, the results obtained with this multi-objective approach are contrasted with the ones computed with a methodology closer to the one traditionally followed in energy efficiency programs. It was found that through a multi-objective approach the selected measures selected differ from the ones obtained with the other methodology, because with the former approach the life cycle performance of the measures is explicitly addressed.

Keywords: Energy Efficiency, Multiple Benefits, Multi-objective Programming, Portuguese Residential Sector, Genetic Algorithm

Resumo

Tem sido amplamente reconhecido que a adoção de medidas eficientes em termos energéticos é extremamente importante para reduzir o consumo de energia e as emissões de gases com efeito de estufa, dimininuindo também a fatura energética e aumentando a segurança energética. Além disso, o investimento em medidas eficientes em termos energéticos também implica outros benefícios relevantes que muitas vezes são negligenciados. Neste contexto, o presente trabalho procura desenvolver uma abordagem holística, considerando explicitamente múltiplos benefícios associados a várias medidas eficientes em termos energéticos. Neste âmbito, foi construído um modelo multi-objectivo, que permite obter soluções eficientes que contemplam portfolios de medidas energeticamente eficientes aplicadas ao sector residencial português. Este modelo considera cinco funções objetivo: a maximização do rácio poupança-investimento (SIR), a minimização do tempo de reembolso do carbono (CPBT), a minimização do custo da energia conservada (CCE), a minimização do risco calculado através da utilização dos pontos de vista dos diferentes peritos e a minimização da diferença para o orçamento disponível. As soluções para o modelo são então calculadas através de uma implementação ajustada baseada no *Non-Dominated Sorting Genetic Algorithm*. Finalmente, os resultados obtidos com esta abordagem multi-objectivo são contrastados com os calculados com uma metodologia mais próxima da tradicionalmente seguida em programas de eficiência energética. Constatou-se que numa abordagem multi-objectivo as medidas selecionadas diferem daquelas que foram obtidas com a outra metodologia, pois contemplam a análise do desempenho de ciclo de vida.

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Palavras-chave: Eficiência Energética, Benefícios Múltiplos, Programação Multi-objetivo, Setor Residencial Português, Algoritmo Genético

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Acronyms

AUGMECON2 - Efficient Epsilon-Constraint Method
AVERT – AVoided Emissions and geneRation Tool
BCR – Benefit-Cost ratio
CCE – Cost of Conserved Energy
CEC – California Energy Commission
CFL – Compact Fluorescent Lamp
COMBI - Calculating and Operationalising the Multiple Benefits of Energy Efficiency
CO2eq – Carbon Dioxide Equivalent
CPBT – Carbon Payback Time
CPUC – California Public Utilities Commissions
DHW – Domestic Hot Water
EDP – Energias de Portugal
EPBT - Energy Payback Time
EPS – Expanded Polystyrene Foam
EU – European Union
EUROSTAT - Statistical Office of the European Communities
EEF – Energy Efficiency Fund
GA – Genetic Algorithm
GAMS - General Algebraic Modeling System
GAINS - Greenhouse Gas-Air pollution Interactions and Synergies
GDP – Gross Domestic Product
GHG – Green House Gases
GWP – Global Warming Potential
HVAC – Heating Ventilation and Air Conditioning
ISF – Innovation Support Fund
LCA – Life Cycle Assessment
LEAP – Leadership for Energy Action and Planning
LED – Light Emitting Diode
MCDA – Multi-criteria Decision Aiding
MFA – Material Flow Accounting
Mtoe – Megaton of oil equivalent
NAPEE – National Action Plan for Energy Efficiency
NECP – National Energy and Climate Plan
NPCC – National Program for Climate Change

NPV – Net Present Value

NREAP – National Renewable Energy Action Plan

NSGA – Non-Dominated Sorting Genetic Algorithm

PCF – Portuguese Carbon Fund

PPEC – Plano de Promoção à Eficiência no Consumo

PRIMES - Price-Induced Market Equilibrium System

PVC – Polyvinyl Chloride

SIR – Savings to Investment Ratio

SPM - Standard Practice Manual

SSP - Shared Socioeconomic Pathways

TOPSIS - Technique for Order of Preference by Similarity to Ideal Solution

VaR – Value-at-Risk

XPS – Extruded Polystyrene Foam

1. Introduction

1.1 Context

The International Energy Agency anticipates that in 2030, half of the reduction on Greenhouse gas (GHG) emissions will come from the adoption of efficient technologies. In this context, the promotion of energy efficiency policies makes it possible to reduce both energy consumption and GHG emissions in a less costly and more effective manner, ensuring the quality of energy services [1], [2], [3] . For this reason, energy efficiency has become a central issue in terms of energy and environmental policies in Europe [4], which in 2012 approved the Energy Efficiency Directive (2012/27/EU). With this Directive, a series of measures were approved so that by 2020, the overall energy consumption in the European Union (EU) would be less than 1,483 million tons of oil equivalent (Mtoe) of primary energy, or 1,086 Mtoe of final energy [5]. In January 2020, data from the Statistical Office of the European Communities (EUROSTAT) indicated that the primary energy consumption was 5.8% above the 2020 targets in 2018 and the final energy consumption was also 3.5% above the established goals [6]. These facts worried most European policy-makers because they showed that by 2020, the national and international efforts wouldn't be enough to reach the targets imposed by the Energy Efficiency Directive. The COVID crisis significantly impacted the economy and led to a decrease of energy consumption in 2020. Nevertheless, if the European economy does not become more energy efficient, the recovery will probably lead to a rebound in energy consumption, something that is highly unwanted [6].

In December of 2018, the Energy Efficiency Directive was updated. The main novelty introduced regards the new EU energy efficiency target for 2030 of at least 32.5%, followed with a clause for a revision by 2023. This target is rendered into a final energy consumption of 956 Mtoe and/or primary energy consumption of 1,273 Mtoe in the EU-28 in 2030. Knowing this, the EU established that each Member State needs to create and assemble a 10-year integrated national energy and climate plan (NECP) for 2021-2030 [7]. In this plan, the contributions for the 2030 targets for energy efficiency, GHG emissions and renewable energy need to explicitly be mapped. Taking this international initiative into a national landscape, the NECP has been built and established [8]. This national program took a series of measures and initiatives to reach the goals demanded by the EU. Consequently, energy efficiency promotion programs are extremely important.

In order to understand how these programs assess the measures to be selected for funding we need to look back at 1970, when the California Public Utilities Commission (CPUC) and California Energy Commission (CEC) began to promote programs of load conservation and management. By this time, the criteria for the selection of the energy efficient measures were fundamentally based on their costs, ignoring everything else. However, in 1983 new evaluation criteria started to be included in these programs based on the application of a series of tests that stood by different types of perspectives, giving birth to the Standard Practice Manual (SPM) [9]. The SPM was revised in 1987-88 and, in 2001, the SPM underwent some changes due to the cumulative effects of changes in the natural gas and electricity industries. This latter version corresponds to the version used today [9].

Before the 2030 action plan, to achieve the goals established by the European legislation, the National Action Plan for Energy Efficiency (NAPEE) recommended subsidized programs with the objective of financing highly energy efficient measures. The methodologies normally considered in this type of programs follow a benefit-cost and/or effective cost analysis [10]. Since the 1980s, this type of methodologies has been used extensively to respond to energy efficiency initiatives, after the publication of the tests proposed by the CEC and the CPUC [9]. These tests have become universal being used by several entities and utilities worldwide [11]. Reference [12] proposed a specific methodology for Europe, which despite being analogous to the methodology used in CPUC, it incorporated some novelties. Among them, the selection of perspectives and impacts are highlighted in the evaluation procedure. This would make the methodology adjustable to the various possible situations and it would allow the incorporation of non-monetary impacts.

However, the identification, selection and evaluation of the combination of energy efficient measures to be funded by public bodies is a complex process. The investment in energy efficient actions has subsequent multiple benefits, such as economic, environmental and social, and can lead to a series of social and health benefits such as reduced mortality and winter morbidity for example. Furthermore, there it is also the necessity of accounting for the different types of buildings, and the different preferences of the stakeholders [13].

Therefore, it is necessary to support public decision-makers with innovative methodologies in the process of selecting the energy efficient measures for the residential sector that should be funded. Nevertheless, in order to fully understand the potential outcomes of assessing these energy efficient measures, it is important to contemplate an approach that includes environmental sustainability, based on Life Cycle Assessment (LCA), which covers the full life cycle of the proposed measure, and not just the equipment manufacturing and/or building operation phases [14].

1.2 Aim

The main objective of this dissertation is to answer both research questions proposed in the beginning of this work: “To what extent will it be useful to consider other benefits when analysing portfolios of energy efficiency measures?” and “To what extent does the use of different approaches for assessing and selecting portfolios of energy efficiency measures lead to different results?”. To find these answers we identified and evaluated energy efficient measures for residential buildings from a multiple benefits perspective. Hence, a multi-objective programming model has been built with this purpose. Then, a genetic algorithm based on the Non-Dominated Sorting Genetic Algorithm II (NSGA-II), but with different genetic operators has been used to obtain the efficient portfolios of energy efficient measures that could be selected for funding. The different portfolios that were obtained were analyzed and finally they were compared to an approach closer to the one traditionally considered in this sort of problems.

1.3 Work Structure

This document is arranged into six chapters. In the first Chapter, the present dissertation is explained and framed. Subsequently, in the second Chapter, a literature review is carried out on the multiple benefits brought by energy efficiency, its promotion support programs and how the multi-objective evaluation is being made. Afterwards, in the third Chapter, the Portuguese residential sector is characterized and the adopted measures to be evaluated are described.

The fourth Chapter contains the methodology used throughout the present work, more specifically, the mathematical model and the genetic algorithm implementation.

Finally, in Chapters five and six, the analysis of the results, the main conclusions and future work developments are discussed.

2. Literature review

In this chapter the current main national energy efficiency promotion programs will be briefly described as well as the SPM.

Finally, the current approach that is being used to assess and select energy efficiency actions to be implemented will also be addressed.

2.1 Energy Efficiency Promotion Programs

In order to meet the expectations set by the EU, the Portuguese government in coordination with the Directorate General of Energy and Geology created the NECP which states the lines of action for the 2021-2030 horizon.

This plan guarantees the coherence between policies in the energy and climate sectors to reach the targets set for 2030. It establishes national objectives for the GHG emissions, renewable energy and energy efficiency, as well as it substitutes the ongoing national plans, specifically the National Renewable Energy Action Plan (NREAP), the National Program for Climate Change (NPCC), and the National Action Plan for Energy Efficiency (NAPEE) [8].

To meet the goals regarding energy efficiency, there needs to be a 32.5% reduction of primary energy, as well as a 40% reduction in GHG emissions compared to 1990.

From Figure 2.1, it is possible to see according to the green line that a 35% reduction of the consumption of primary energy is required in relation to the Price-Induced Market Equilibrium System (PRIMES) 2007 Business As Usual scenario to attain the required energy efficiency target. This means that to achieve the energy

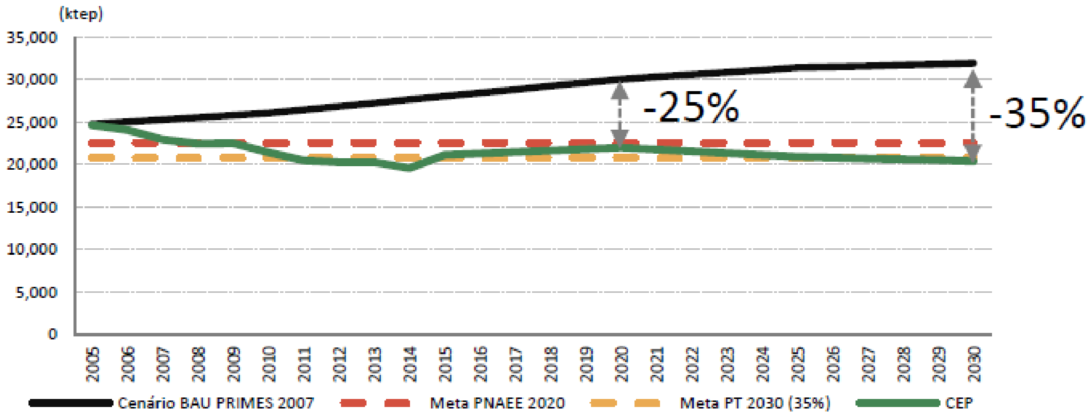

Figure 2.1 – NECP Energy Efficiency goal: Primary Energy Consumption [8]

efficiency target, Portugal must reach a primary energy consumption of 20.4 Mtoe by 2030 [8].

Most national programs follow, in general, the methodology used in the SPM, which, in short, assesses energy efficiency measures by calculating cost-effectiveness from different perspectives. In this context, the Programa de Promoção à Eficiênca no Consumo (PPEC) aims to promote and select energy efficient measures, which contribute to reduce electricity consumption or to manage loads. This plan also promotes measures that contribute to the dissemination of the adoption of rational and efficient behaviors and decisions in energy consumption [15].

In addition to the PPEC, there are more funds created to support projects and programs to foster the adoption of energy efficiency measures, with emphasis on the following:

- **Portuguese Carbon Fund (PCF)**: Created by Decree-Law no. 71/2006, of of March 24th, designed to support, among others, projects that lead to the reduction of GHG [16].

- **Innovation Support Fund (ISF):** Created by Order No. 32276 - A / 2008, of December 17th, which also approved its Management Regulation, subsequently amended by Order No. 13415/2010. In Order No. 5727/2013 the scope of the ISF was extended to include investment projects in energy efficiency [17].

- **Energy Efficiency Fund (EEF)**: Created by Decree-Law no. 50/2010, of May 20th, and regulated by Ordinance no. 26/2011, of January 10th, intended to support the measures of the National Action Plan for Energy Efficiency (NAPEE) [18].

2.1.1 Standard Practice Manual

From Table 2.1, it is possible to see that the cost-effective tests considered in the SPM are divided into four groups of different perspectives: the participant, the ratepayers (customers), total cost of resources and cost from the point of view of the program manager.

Table 2.1 – Effectiveness cost tests adapted from SPM [9]

Participant	
Primary	**Secondary**
Net Present Value - NPV (all participants)	Discounted Payback (years) Benefit-cost ratio (BCR) Net Present value (average Participant)
Ratepayer Impact Measurement	
Lifecycle revenue impact per Unit of energy (kWh) or demand customer (kW) NPV	Lifecycle revenue impact per unit Annual revenue impact (by year, per kWh, kW, or customer) First-year revenue impact (per kWh, kW, or customer) BCR
Total Resource Cost	
NPV	Leveled cost (cents or dollars per unit of energy or demand) Societal (NPV, BCR)
Program Administrator Test	
NPV	BCR Leveled cost (cents or dollars per unit of energy or demand)

- **Participant's Test**

The participant's test measures the quantifiable benefits and costs for the program's participant. In this test the benefits related to the capital saved, and for the case of fuel replacement programs, the level of operating costs of unused equipment, are considered. The economic indicators used are the period of return (payback) of the invested capital, the NPV and the BCR.

Despite providing the program's benefit/s to the participant, none of the indicators used in this test allows to capture the complexity of the decision problem, particularly with regard to management investments on the demand side, making the rest of the tests relevant and a valid requisite [9].

- **Ratepayer impact measurement test**

This test allows measuring the return from the costumers' perspective due to the operating costs related to the application of the program. The rates of return depend on the revenues generated by the implementation of the measures that constitute the program and the total costs of that implementation. The benefits that this test aims at evaluating are the avoided costs of energy supply, namely the reduction of costs in transmission, distribution, generation and capacity in periods when the load has been reduced and the increase in revenues when the load has been increased.

These benefits are expressed by the impact on revenues according to the life cycle of the measures adopted, annual revenues, benefit-cost ratios and NPV. This test also has the advantage of being the only one that makes a comparative analysis of the revenues, costs and benefits resulting from the implementation of energy efficiency measures. Nevertheless, it has the disadvantage of presenting some uncertainty inherent in these results, as they depend on long-term projections that are difficult to quantify [9]. Uncertainty is commonly not assessed in these programs, therefore in this dissertation our model includes a risk measure which reflects the opinions provided by distinct experts inherent to the adoption of the energy efficient measures under scrutiny.

- **Total resource cost test**

It measures the net costs of the demand-side management program in relation to the total costs of the program and represents a combination of the effects of a certain program on both participating and non-participating customers. In a way, it is the sum of the benefits of the two previous tests. The benefits that this test intends to evaluate are the costs avoided in the supply, the reduction of costs in transmission, distribution, generation and capacity in the periods when there is reduction of the load, that is, the same as the previous test.

The great advantage is that this test includes total costs and has the potential to capture a wide range of benefits [9].

- **Cost test to the program administrator**

This test is very similar to the previous test, but the costs are assessed from the point of view of the program administrator, not including the costs incurred by the participants.

In the next section, the PPEC is described as it follows some of the SPM foundations to select and evaluate its energy efficient measures, being based on cost-effectiveness tests [19].

2.1.2 Plano de Promoção à Eficiência no Consumo

Within the scope of PPEC, tangible and intangible measures are promoted. Tangible measures consist of installing equipment with an efficiency level higher than the market standard, thus achieving measurable consumption reductions and at the same time providing the same or better service. Intangible measures consist of the dissemination of information about good practices in the efficient use of electric energy, aiming to promote changes in behavior, and therefore will not be addressed in detail in this work [19].

- **Tangible Measures**

To assess the social value of each tangible measure, a social test is carried out, which consists of calculating the NPV from a social point of view. Thus, only measures of the tangible type that have a positive NPV are eligible for financing under the PPEC. After passing the social test, the measures for each market segment are ranked in decreasing order of merit, according to a set of technical-economic criteria [19].

$$\mathrm{NPV} = \sum_{t=0}^{n} \frac{Bs_t - Cs_t}{(1+i)^t} \qquad (2.1)$$

BSt – Total benefits associated with the consumption efficiency measure in year t;

CSt - Total costs associated with the consumption efficiency measure in year t;

i - Discount rate; n - Lifespan;

The benefits, from a social perspective, are given by the environmental benefits and the avoided costs of supplying electricity. Costs, from a social perspective, include costs financed by both participating consumers and electricity consumers in general (portion financed by PPEC), either by promoters or by other entities [19].

Then, every measure is ranked through its Benefit-Cost Ratio (BCR) value, which is a common indicator to rank the measures that display different amounts of investments and lifespans. This BCR relates the value of the current value of the benefits with the current value of the investment costs, which must be calculated through the following equation [19]:

$$\mathrm{BCR} = \frac{\sum_{t=0}^{n} \frac{Bs_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{Cppec_t}{(1+i)^t}} \quad (2.2)$$

BSt – Total social benefits associated with the consumption efficiency measure in year t;

Cppect - Total costs from PPEC's perspective, associated with the efficient measure, in year t;

i - Discount rate; n - Lifespan;

- **Example of tangible measures for the residential sector within PPEC 2017-2018:**

HEAT PUMPS FOR DHW IN RESIDENTIAL BUILDINGS AND FLOW REDUCERS II

This measure promotes the installation of 1,800 Heat Pumps for Hot Sanitary Waters (DHW), through the replacement of electric water heaters and the application of flow reducers in showers and taps, in order to reduce the consumption of electricity in the heating of sanitary waters.

The target consumers of this measure are all those who belong to the residential sector, which have a DHW production system of the type of electric water heater and whose DHW consumption can be satisfied through equipment with a storage capacity of up to 110 liters [19]. Table 2.2 provides data on the characteristics of heat pumps usually installed on residential buildings.

Table 2.2 – Technical characteristics and costs table of heat pumps [19]

Lifespan (years)	Annual avoided consumption (kWh)	Number of Interventions	PPEC Cost (€)
20	3 167 343	1800	1 139 133

REPLACE YOUR LAMPS WITH LEDS

This measure promotes the use of light-emitting diode lighting equipment - LEDs, through the replacement of E14 and E27 halogen lamps. The target consumers of this measure are all residential consumers. The consumer will be able to obtain LED lamps at EDP stores, having to deliver halogen lamps at the same proportion, in a logic of "exchange for exchange", and fill out a questionnaire. LED lamps will not be free but will have a significant discount in the order of 80% compared to market prices [19] – see Table 2.3.

Table 2.3 – Technical characteristics and costs table of LED lamps [19]

Lifespan (years)	Annual avoided consumption (kWh)	Number of Interventions	PPEC Cost (€)
20	3 285 000	100 000	325 000

EFFICIENT HEATER AND FLOW REDUCERS

This measure promotes the installation of 1,500 efficient electric water heaters in the residential segment, through the replacement of traditional electric water heaters and the application of flow reducers in showers and taps, in order to reduce energy consumption in heating sanitary water [19] – see Table 2.4.

Table 2.4 – Technical characteristics and costs table of Efficient Heater and flow reducers [19]

Lifespan (years)	**Annual avoided consumption (kWh)**	**Number of Interventions**	**PPEC Cost (€)**
20	1 339 193	1500	247 500

LED IN THE RESIDENTIAL SECTOR

This measure promotes the installation of highly efficient LED lamps in replacement of lamps of any technology, by direct exchange. The scope of intervention lies in the replacement of 100,000 low-efficiency lamps, with a predominance of 50 W dichroic halogen lamps, installed inside each dwelling and in the common access areas of condominiums, which work on a day-to-day basis. Thus, it is planned to replace 100,000 dichroic 50 W halogen lamps GU10 and GU5.3 (50,000 each) with dichroic LED lamps of 5.5W (GU10) and 8W (MR16) – see Table 2.5.

Table 2.5 - Technical characteristics and costs of LED lamps [19]

Lifespan (years)	**Annual avoided consumption (kWh)**	**Number of Interventions**	**PPEC Cost (€)**
20	6 314 500	100 000	669 337

IMPROVING THE ENVIRONMENT IN RESIDENTIAL BUILDINGS

This measure refers to the intervention in the opaque façades of the existing residential building stock through the thermal insulation of roofs or façades or any other action that leads to a reduction in the thermal transmission coefficient of the opaque façades and thus allows the reduction of the need of heating and/or cooling, and leads to a reduction in electricity consumption and CO2 emissions associated with the air conditioning of the home. The scope of intervention refers to the thermal insulation of the façade and of the roofs of residential buildings, constituted in total or horizontal property, with the latter being able to cover the entire building or just one or more of the autonomous fractions that compose it – see Table 2.6.

Table 2.6 – Technical characteristics and costs table of residential buildings improvements [19]

Lifespan (years)	Annual avoided consumption (kWh)	Number of Interventions	PPEC Cost (€)
20	2 534 630	1200	611 233

2.2 The multiple benefits of energy efficiency

The investment in energy efficiency can bring a wide range of benefits to the stakeholders [20].

The studies involving multiple benefits in energy efficiency are disperse, they vary a lot with the magnitude of impacts, and they have limitation on the coverage regarding some sectors, technologies, geography, and politics. The big challenge on the quantification of these benefits is the dependency of context, meaning that the quantification varies between technologies, sectors, end-users, country location and policies. Besides, there are several methods to quantify and monetize impacts of these multiple benefits, and some of these benefits are incredibly hard to quantify [21].

Stakeholders usually like concrete and solid evidence of their money being well spent, so it is understandable why it’s still a challenge to make them believe on some of the benefits due to the lack of data, studies and robust methodologies in the area. Some benefits are simply not studied well enough to be worth of a serious investment, and therefore the level of importance of these multiple benefits in a social and economic development is not well understood [20].

The relevance of these benefits differs according with different perspectives and scenarios, such as national circumstances, and social and economic priorities. Different countries will value these benefits in a different way, and therefore within the national context, different stakeholders will be interested in different benefits. For example, countries under development, with low energy access rates, can use energy efficiency to deliver energy to more customers, and in contrast, countries with universal access rates can use energy efficiency to improve their industrial productivity. Furthermore, to understand the potential of these multiple benefits, it is studied that the benefits brought by the policies applied to the residential sector have the potential to be more powerful and impactful than the direct energetic benefits like consumption reduction. Reinforcing that a multiple benefit analysis can and should be adapted to the needs and challenges of each specific scenario [21].

There are several issues at stake in this kind of analysis because some of these benefits are indirect or are a product of a chain of events. Therefore, it can be difficult to clearly identify the connection between an energy efficient measure and all of its benefits. The impacts can occur simultaneously at various economical levels - from individual citizens, households, to individual sectors – on at a national or international scale. There is also a problem when it comes to energy efficiency enhancements. Some of these improvements can be used to access to more energy services instead of achieving the reduction in the consumption goal. A multiple benefit analysis can help understand these rebound effects, where they come from and their causes [21].

Another problem is that if we aggregate these impacts, double counting and interactions can occur and some can be controversial due to methodological challenges and ethical issues involved in the computation of the value to assign to life and health, for instance [21].

To better understand these benefits, they are usually divided into three groups of aspects: energy, social/health and economic. Furthermore, these three groups are also sub-divided by some researchers into two categories, primary and secondary [22].

When we think about direct energy benefits brought by energy efficiency measures, we immediately think about energy savings, but, for example, it can also help reducing the general energy cost through time, avoiding power generation and building new power plants. The secondary benefits may indirectly increase the reliability and security in the energy system for example [22].

It is known that electricity generation based on fossil fuel combustion is a source of air pollution which is a risk for human health due to respiratory complications caused by particles from pollutants gases and ground-level ozone. In some countries this form of combustion is the biggest source of GHG emissions, highlighting the interactions between the three big groups of benefits, since improving energy efficiency can reduce the generation based on fossil fuel combustion and, at the same time, reduce adverse health and environmental complications. Furthermore, reducing these pollutants will improve air quality, which by itself, implies direct and immediate health benefits.

Looking deeper into the economic benefits, most of the health and electricity benefits will indirectly affect the economy. These include savings in energy costs, new jobs, more profits to the companies which adopt energy efficiency policies and promoting a bigger and better productivity since employers will miss fewer workdays due to health complications [22].

The relationship between these different areas of benefits are well represented in the following chart adapted from [22]:

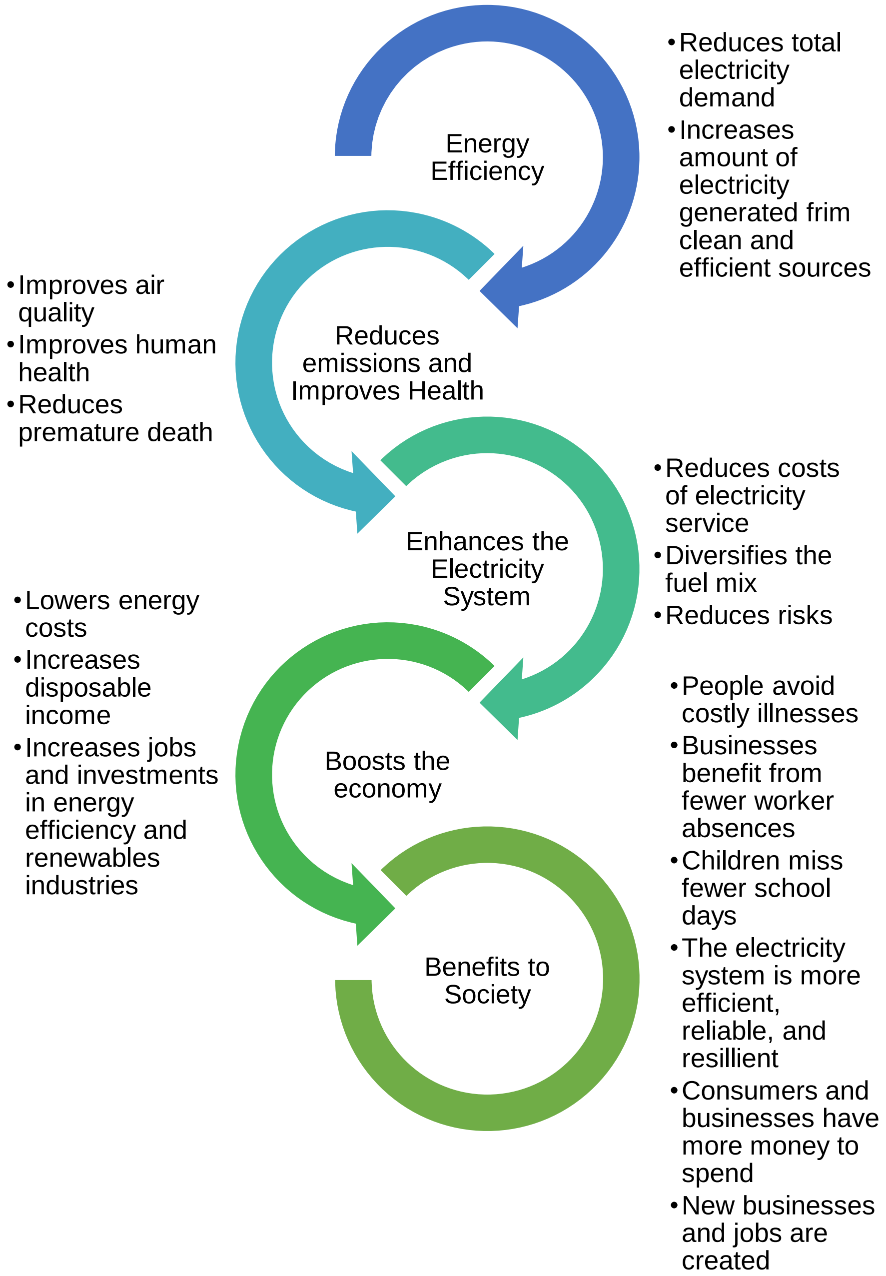

Figure 2.2 – Multiple Benefits Relation Scheme (adapted from [22])

Finally, a review of the scientific literature regarding multiple benefit analysis in energy efficiency can be found in Table 2.7:

Table 2.7 - Multiple Benefits of Energy Efficiency Studies Compilation

Publications	Measures	Benefits	Methods	REF
The macro-level and sectorial impacts of EE policies	5 different scenarios considering different levels of ambition; mostly lighting and residential measures	➔ Economy and labor market; ➔ Health; ➔ Environment impacts; ➔ Social aspects; ➔ Public Budget; ➔ Industrial competitiveness; ➔ Gross Domestic Product (GDP); ➔ Employability.	➔ PRIMES Model ➔ Analysis to the macroeconomic model E3ME ➔ Greenhouse Gas-Air pollution Interactions and Synergies (GAINS) for health impacts	[23]
A comprehensive indicator set for measuring multiple benefits of energy efficiency	➔ MURE database for energy efficiency measures	➔ Energy savings ➔ Reduced GHG emissions ➔ Macroeconomic effects (impacts on economic growth, innovation, competition) ➔ Health benefits ➔ Poverty alleviation and employment	➔ ODYSEE for indicators ➔ Top-down and bottom-up modelling	[24]
The Multiple Benefits of the 2030 EU Energy Efficiency Potential	➔ Building improvements ➔ Space Heating ➔ Space cooling ➔ Domestic hot water	➔ Air pollution and its effects to human health, ecosystems and buildings;	➔ GAINS MODEL; ➔ Material Flow Accounting (MFA) ➔ Carbon Footprint: LCA	[25]

	➔ Lightning	➔ Social well-being: comfort, health and productivity; ➔ Biotic and non-biotic resources; ➔ Energy system and security; ➔ Macroeconomics: employment, economic growth and public budget	➔ Calculating and Operationalising the Multiple Benefits of Energy Efficiency (COMBI) model; ➔ Input/Output (I/O) analysis; ➔ Budgetary semi-elasticities ➔ General equilibrium;	
Capturing the Multiple Benefits of Energy Efficiency, IEA	No mention	➔ Energy savings; ➔ GHG emissions energy security, delivery and prices improvement; ➔ Macroeconomic impacts; ➔ Industrial productivity; ➔ Poverty alleviation, health and social well-being; ➔ Local Air pollution and resources management; ➔ Public budget;	➔ Benefit-Cost Analysis; ➔ Payback period; ➔ Decisive multi-criteria analysis; ➔ Fiscal activity multipliers; ➔ Decomposition analysis; ➔ Conservation supply curves; ➔ I/O analysis; ➔ System of equations ➔ Bottom-up engineering models	[20]
Widening the perspective – An approach to Evaluating the MB of the 2030 EU energy efficiency potential	➔ Building improvements ➔ Space Heating ➔ Space cooling ➔ Domestic hot water ➔ Lightning	➔ Air pollution and its effects to human health, ecosystems and buildings; ➔ Social well-being: comfort, health and productivity; ➔ Biotic and non-biotic resources; ➔ Energy system and security; ➔ Macroeconomics: employment, economic growth and public budget;	➔ Socio-economic modeling; ➔ General Equilibrium; ➔ Leadership for Energy Action and Planning (LEAP) model; ➔ Multi-Step Framework; ➔ GAINS model; ➔ EcoSense Web ➔ LCA; ➔ MFA;	[21]

Quantifying the Multiple benefits of Energy Efficiency and renewable energy	No mention	➔ Avoided costs from generating or purchasing wholesale electricity; ➔ Deferred or avoided costs of expanding the capacity of power plants ➔ Better reliability and power quality; ➔ Reduced risks ➔ Improvements in air quality and public health; ➔ Domestic, commercial, construction, operating and administrative costs	➔ GE MAPS; ➔ AURORA; ➔ PROMOD IV; ➔ Integrated Planning Model; ➔ PLEXOS; ➔ National Energy Modeling System; ➔ AVoided Emissions and geneRation Tool (AVERT);	[26]
Estimating the Multiple Benefits of Building Energy Efficiency in GCC Countries Using an Energy Productivity Framework (KAPSARK)	➔ Low-cost energy efficiency measures; ➔ Intallation of thermostats ➔ Ligthning ➔ Window and glazing replacement; ➔ Installation of daylight control systems	➔ Avoided energy; ➔ Value of the avoided energy consumption; ➔ Value of avoided generation capacity; ➔ Avoided carbon emissions; ➔ Discounted payback period for all benefits	No mention	[27]
Recognizing the value of energy efficiency's Multiple Benefits	➔ Heating ➔ Ventilation ➔ Heating Ventilation and Air Conditioning (HVAC) systems ➔ Water Heating	➔ Less expenses with water and sewage; ➔ Less maintenance househould wise; ➔ Less maintenance equipment and appliance wise; ➔ High comfort levels	➔ Algorithm based on water savings for each device, and costs of water and sewage services; ➔ Questionnaires methods have been used to report incidence of symptoms or occurrences of	[28]

	➔ Shell improvements (air sealing and insulation)	➔ Less noise, quieter indoor environment; ➔ Security improvements(less fires, less CO poisoning) ➔ Higher property value; ➔ Less diseases, off-days;	specific pre and post retrofit health problems	
Identification and Quantification of Multiple Benefits of Energy Efficiency Plans (Consulting)	Consulting	➔ Lifetime direct GHG emissions mitigated; ➔ Direct and Indirect GHG emissions avoided; ➔ Improvements of sustainability in the energy system; ➔ Economic and social development; ➔ Increased prosperity and benefits in mortality, morbidity and comfort;	➔ Benefit-Cost Analysis; ➔ Multi-criteria analysis (MCDA);	[29]
More than energy savings: quantifying multiple impacts of energy efficiency in Europe	➔ Building improvements ➔ Space Heating ➔ Space cooling ➔ Domestic hot water ➔ Lightning	➔ Air pollution and its effects to human health, ecosystems and buildings; ➔ Social well-being: comfort, health and productivity; ➔ Biotic and non-biotic resources; ➔ Energy system and security; ➔ Macroeconomics: employment, economic growth and public budget;	➔ EUROSTAT, PRIMES ➔ ODYSSEE ➔ GAINS, EcoSense Web ➔ MFA, LCA; ➔ I/O ➔ Copenhagen Economics Global Climate and Energy Model;	[30]
Multiple Benefits of Industrial Energy Efficiency	IEA reference	➔ Increased and more reliable production; ➔ Improved product quality;	IEA reference	[31]

– Lessons Learned and New Initiatives		➔ Increased equipment life; ➔ Less processing time; ➔ Less raw material to use; ➔ Less maintenance, cooling requirements, labor requirements and need for engineering controls; ➔ Increased work safety and less noise; ➔ Improvements in air quality, temperature control and lighting; ➔ Lower water costs, less toxic waste		
Multiple Benefits through Smart Home Energy Management Solutions – A simulation-based Case Study of a Single-Family-House in Algeria and Germany	Simulation, case studies using households with smart home technologies; 3 scenarios: 1 - baseline 2 - Low-cost 3 - extended Each scenario has different types of energy control and related equipment ;	➔ Air pollution and its effects to human health, ecosystems and buildings; ➔ Social well-being: comfort, health and productivity; ➔ Biotic and non-biotic resources; ➔ Energy system and security; Macroeconomics: employment, economic growth, and public budget	➔ Macroeconomic tools: Partial and general equilibrium; ➔ I/O Analisys;	[32]

After further inspecting these studies it is clear that the discoveries regarding the multiple benefits of energy efficiency are disperse, as they vary a lot with the magnitude of the impacts and have flaws regarding the coverage of some sectors, geography and political impacts. There is a variety of methods that try to quantify and monetize the multiple benefits of energy efficiency impacts, but their application is highly difficult, and varies from method to method and there are data limitations.

Nevertheless, [21] refers that for example the impacts of the reduction of pollution in health, ecosystems, crops and built environments are completely integrated and connected. The authors explain that climate changes and atmospheric pollution are phenomena that are intrinsically related to one another. However, these two aspects are still studied separately. Therefore, in order to trigger synergies, avoid bad results and secure cost effective policies, it is important that the problem is viewed as a whole. It is clear by now that fossil fuel combustion is the center of both problems, so reducing energy consumption without compromising the quality and quantity of energy services would offer double dividends regarding both problems. Reference [21] also mentions impacts on social welfare, more precisely on energy poverty, comfort, and health. These impacts caused by energy efficiency interventions are relevant mostly on urban transport and on residential sectors. Since energy efficiency in the residential sector is the main focus of this dissertation, and because [21] mentions the importance of insulation measures and retrofits in heating, cooling and ventilation technologies, we will assess 44 insulation measures applied to the Portuguese residential sector that will be further detailed. Reference [21] states that the largest benefits on the residential sector happen when the energy efficiency interventions refer to low-income groups, especially those who suffer from energy poverty – a condition defined by the inability of a certain household to secure a social and material level of necessary energy services. Thus, highlighting the need to fund energy efficiency programs by the government.

The insulation measures also have direct influences on health, as they have the potential to benefit mental and physical health from those who suffer from poor conditions in their households, such as cold, humidity and so on. If we increase indoor temperatures, in the heating season, the general comfort will also increase, as better insulation will also improve resistance to exterior noises. The general household income will also rise as savings in the energy bill take place.

Reference [20] states that obtaining energy savings is the same as calculating the energy intensity, which is given by the ratio between final consumption of energy and GDP. Also, energy savings affect the energy systems in other ways, such as the avoided costs related to the construction of new power plants.

2.3 Multi-Objective Evaluation in Energy Efficiency

This section reviews multi-objective models specifically built to help decision-makers assess and select the energy efficient measures to be adopted or funded by public bodies, through the consideration of portfolio models – see Table 2.8.

In a multi-objective context rather than having optimal solutions, we have efficient solutions (or non-dominated solutions). A solution is called non-dominated or efficient when there is no other solution that dominates it, i.e., that it is not worse than it in all objective functions, and simultaneously, it is better than it in at least one objective function [33], [34]. Formally:

For a given multiple objective problem, where:

$$\text{minimize/maximize: } f_m(x), m = 1,2, \dots, M$$

$$\text{Subject to: } g_j(x) \geq 0, j = 1,2, \dots., J$$

$$h_k(x) = 0, k = 1,2, \dots, K$$

$$x_i^{(L)} \leq x_i \leq x_i^{(U)}, i = 1,2, \dots, n$$

A solution is a vector of n decision variables:

$$x = (x_{1,} x_2, \dots, x_n)$$

Where the problem is subjected to J inequality constraints and K equality constraints. Additionally, each variable has an upper and/or lower bound associated with it. In the following definitions M is the number of objective functions to be considered and the set Ω is the feasible region or “search space”:

- **Definition 1 – Pareto Dominance**

A vector y dominates another vector x (denoted as $y \preceq x$) if and only if $f_m(x) \leq f_m(y)$ for every $m \in \{1,\dots, M\}$ and $f_m(x) < f_m(y)$ for at least one index $m \in \{1,\dots, M\}$.

- **Definition 2 – Non-dominated Solution**

A solution $x^* \in \Omega$ is non-dominated if there is no $x \in \Omega$ such that $x \preceq x^*$.

- **Definition 3 – Pareto Optimal Set**

For the given multiple objective problem, the Pareto optimal set $P^* = \{ x \in \Omega \mid \nexists\, x' \in \Omega, x' \preceq x\}$.

- **Definition 4– Pareto Optimal Front**

For the given multiple objective problem and its Pareto optimal set P^*, the Pareto optimal front, PF^*, is defined as $PF^* = \{ f(x) \in \mathbb{R}^M \mid \boldsymbol{x} \in P^*\}$, where $\mathbb{R}^M$ is the objective space.

Table 2.8 – Multiple Objective Optimization Studies Compilation

Publications	Objectives	Constraints	Tools to deal with uncertainty	EE Goals	REF
Portfolio-based eletricity Generation Planning: Policy Implications For Renewables and Energy Security	➔ Increasing renewables share; ➔ Use of Mean Variance Portfolio which focus on risk and return (cost); ➔ Security and sustainability maximization;	➔ Limits to distribution grids; ➔ Policies constraints;,	➔ The relative value of the generation technologies is evaluated through portfolios with alternative resources and not evaluated as alternative resources themselves.	yes	[35]
Investment planning in energy efficiency programs: A portfolio based approach	➔ risk and return;	➔ Public budget ➔ Max number of assets within a portfolio; ➔ Minimum Energy Payback Time (EPBT); ➔ Maximum and minimum capital to be invested; ➔ Short selling is not allowed;	➔ Interval, Stochastic and Fuzzy programming techniques.	yes	[36]
Integrated policy assessment and optimization over multiple sustainable development goals in Eastern Africa	➔ Simultaneously reduce GHG emissions, atmospheric pollution exposure and improve energy access;	➔ Two annual budget constraints are considered for two different scenarios;	➔ Connection of integrated studies and robust portfolio analysis; ➔ Different SSP's (shared socioeconomic pathways)	No	[37]

Promoting energy efficiency investments with risk management decision tools	➔ No objectives have been specified, since it’s a study on how to assess risk; ➔ VaR (Value-at-Risk) is used, so value vs risk is considered;	➔ Liquicity constraints; ➔ Lower bounds of energy prices regarding fossil fuels; ➔ Available budget when applied to developing countries as it helps to reduce energy costs and carbon emissions;	➔ Uncertainty is incorporated by specifying expected values of an investment cost, benefits and equipment lifespan; ➔ R risk factor that reflects the risk regarding the investment; ➔ Monte Carlo Analysis	no	[38]
Identifying optimal technological portfolios for European power generation towards climate change mitigation: A robust portfolio analysis approach	➔ Maximize the GHG reductions that corresponds to a specific budget investment; ➔ Maximize energy security in relation to the allocated budget	➔ Approved applications cumulative cost doesn´t exceeds general budget; ➔ Minimum emissions reduction for each portfolio; ➔ Bounds to control the budget distribution for energy generation technologies	➔ Stochastically with (Efficient Epsilon-Constraint Method) AUGMECON2, using Monte Carlo ➔ General Algebraic Modeling System (GAMS) platform;	yes	[39]

Hedging uncertainty in energy efficiency strategies: a minimax regret analysis	➔ Maximize saved energy after the portfolio implementation;	➔ Two classes of constraints: finance and employability; ➔ Upper bounds relative to budget limit; ➔ Lower bounds relative to job creation;	➔ Uncertain exterior variables for the objective function; ➔ Robust optimization for measure identification, which have good performance regardless the scenario concretization; ➔ Low precision of the energy savings factor	no	[40]
Energy efficiency promotion in Greece in light of risk: Evaluating policies as portfolio assets	➔ Achieve the energy savings goals from NEEAP while costs and risk impacts are minimized; ➔ Portfolio energy savings maximization; ➔ Cumulative portfolio risk minimization;	➔ Max budget definition, available from the Ministry; ➔ Fixed budget for Smart Metering Systems(M16) deployment; ➔ Number of viable technical and theoretical implementations per year and per measure;	➔ Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) model; ➔ Monte Carlo simulation;	yes	[41]

From the literature review conducted it can be established that most of the papers reviewed focus on risk and return, while others tend to minimize GHG emissions and maximize some sort of benefits such as energy security and total saved energy. In this context, reference [41] tries to fulfill the energy savings goals, while it also minimizes the cumulative risks related to the impacts that the implementation of the measures entails. In this study two objective functions are considered: the maximization of the energy savings of the portfolio, and the minimization of the risk of the portfolio.

Regarding the constraints used in these studies, a common constraint across found was the definition of the total budget available for the implementation of the measures. An interesting feature in reference [40] is that no measure can dominate a portfolio, meaning that there is a limit of budget to be applied to each measure, ensuring a certain diversification strategy. Specific bounds to control the budget distribution throughout the energy generation technologies are set, focusing on specific energy sources. For example, the constraint "budget allocation for renewable generation technologies must be collectively equal or superior to 40% of the total budget", guaranteeing that in the case of buying a new technology with a certain budget amount, it is not possible to buy the same technology with another amount of capital. In our work, we follow a similar approach but addressing a set of measures on the residential sector. Furthermore, reference [41] imposed as upper bounds the number of possible interventions of each measure.

Concerning the treatment of risk, reference [41] used the TOPSIS model (Technique for order of Preference to Ideal Solutions), which is a multi-criteria decision analysis method based on the concept that the chosen solution has to have the smallest geometric distance regarding the ideal positive solution and the biggest geometric distance to the ideal negative solution [42]. Since this is a straightforward method, we have adopted it to establish our risk objective function.

3 Adopted Measures

The decision on the choice of measures to be considered in our analysis was based on current renovation needs of the Portuguese residential sector and on the PPEC 2017-2018. According to reference [43] the majority of the Portuguese building stock was built after 1971, more precisely 63.1% was finished between the 70’s and 80’s. Obviously with a building stock this old, an efficient energetic upgrade is needed. Some of the true potential of this upgrade can be captured and understood by comparing the buildings that need refurbishment, which are represented in Figure 3.1, with the information given by the National Institute of Statistics [44]. In 2019, the Portuguese building stock was composed of 3 612 472 buildings and 5 968 354 households [44]. This reflects an increase of 0,23% and 0,24% respectively, when compared to 2018. Meaning that if we consider the ratio between all the residential buildings needing repair the total number of buildings we have $\frac{buiding\ stock\ needing\ repair\ (\sim 957\ 000)}{total\ bulding\ stock\ (3\ 612\ 472)}\ \mathrm{x}\ 100\% \approx 26{,}5\%$” , which is a percentage to be considered.

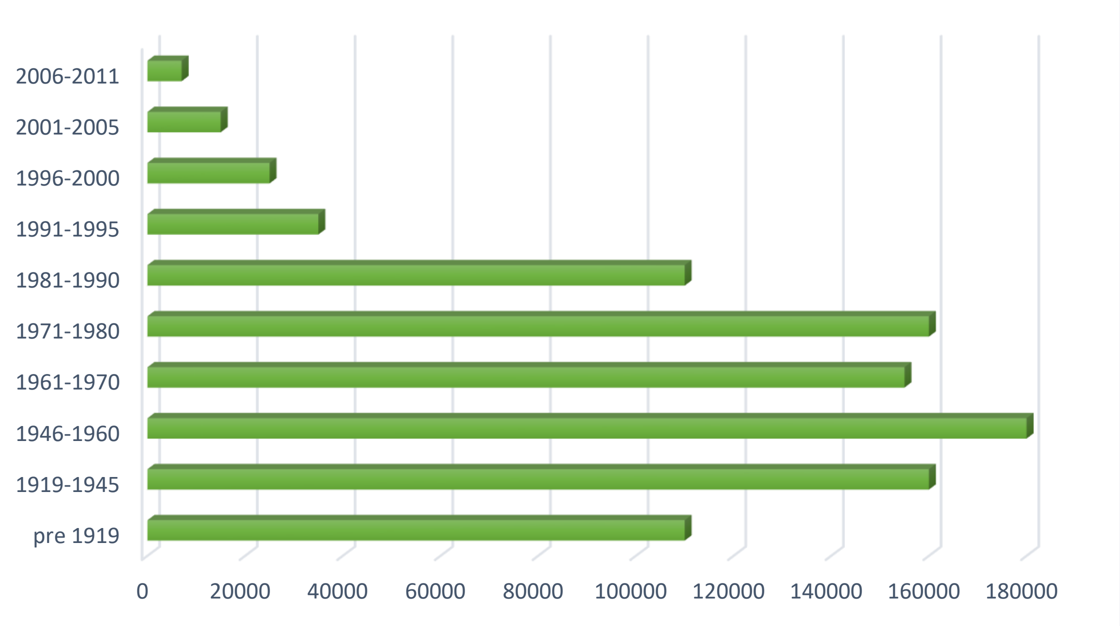

Figure 3.1 - Total building stock needing repair (adapted from [43])

We consider that a building that needs refurbishment is more prone to have its energy performance upgraded.

Hence, the selection of the set of measures to be included in the energy efficiency portfolios covers the replacement of existing technologies. In this context, we have matched the different building construction ages, and its constructions characteristics, as detailed by [45]. The measures were grouped into two different categories: technological measures, such as the replacement of lighting, air conditioning and hot water technologies, and constructive measures concerning the renovation of existing buildings, such as insulation and window improvement.

In this framework, we have considered the following constructive measures to be scrutinized: XPS (Extruded Polystyrene Foam), EPS (Expanded Polystyrene Foam) and PVC frames for double-glazed windows. These measures were indexed as shown in Tables 3.1 and 3.2, by following the same approach in [45], which applied 44 constructive measures according with the building type and age of construction.

Table 3.1 - Measure Indexing (adapted from [45])

Single-Dwelling Buildings				
Era	<1960	1961-1990	1991-2012	>2013
XPS Wall Insulation	1	5	9	13
EPS Wall Insulation	2	6	10	14
XPS Roof Insulation	3	7	11	15
Double-Glaze Windows	4	8	12	16

Table 3.2 - Measure Indexing (adapted from [45])

Multi-Dwelling Buildings								
	2 Facades				**2 Facades and Roof**			
Era	<1960	1961-1990	1991-2012	>2013	<1960	1961-1990	1991-2012	>2013
XPS Wall Insulation	17	20	23	26	29	33	37	41
EPS Wall Insulation	18	21	24	27	30	34	38	42
XPS Roof Insulation	-	-	-	-	31	35	39	43
Double-Glaze Windows	19	22	25	28	32	36	40	44

Furthermore, it is also important to technically characterize these different types of measures in order to assess them regarding their performance and lifecycle impact.

First of all, it is important to understand the lifecycle impact related to each measure, which quantifies the overall impact of resource consumption and environmental emissions at different stages of a product's lifecycle. Concretely, we have considered three different phases: the “cradle-to-gate” phase, the use phase, and the “end of life” phase. The first one represents the very beginnings of the product, from the resource extraction (cradle) to the factory gate (before reaching the consumer). On this type of assessment (partial product life cycle) the “end–of-life phase” or the disposal step, is a recycling process [46]. The Global Warming Potential (GWP) was used to allow comparisons between different gases and how they impact global warming. More concretely it is a representation of how much energy the emissions of 1 ton of a gas will absorb over a given period, relative to the emissions of 1 ton of carbon dioxide (CO2). Hence, the bigger the GWP the more a certain gas warms the Earth compared to CO2 over that period [47]. After internalizing these two concepts we are ready to technically characterize both the constructive and technological measures.

35 mm XPS Insulation

It is a type of insulation material sold in plaques and it is applied to cavity walls. Regarding its lifecycle impact, the data from the Environmental Product Declaration which contains the reference to 1m^2 of XPS was considered [48].

This insulation material has a thermal conductivity of 0.035 W/(m.K), and a density (ρ) of 32kg/m^3. Reference [45] calculated its adapted LCA indicator using the following expression, where $Iadapt$, $dadapt$ and $\rho adapt$ are the adapted LCA indicator, board thickness and density, respectively, and $Iref$, $dref$ and ρref are the reference values for the same parameters:

$$Iadapt = Iref \text{ x } \frac{\rho adapt}{\rho ref} \text{x} \frac{dadapt}{dref} \tag{3.1}$$

Resulting in a computed value for the “cradle-to-gate” GWP impact of 3,14 kgCO2$_{eq}$/m^2 and an end of life stage impact of 3,799 kgCO2$_{eq}$/m^2. So, to link these values to our data for the performance indicators, we have to consider the mean value of the wall/roof area of the building to be upgraded. We have considered the Portuguese building stock [45] and compiled the data on Tables 3.3 and 3.4.

Tables 3.3 - Portuguese Building Stock Characteristics adapted from [45]

Single-dwelling				
Era	<1960	1961-1990	1991-2012	>2013
Floors	1	1	2	2
Facade 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

Tables 3.4 - Portuguese Building Stock Building Characteristics adapted from [45]

Multi-Dwelling								
	2 Outer Facades				**2 Outer Facades and Cover**			
Era	<1960	1961-1990	1991-2012	>2013	<1960	1961-1990	1991-2012	>2013
Facade 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

For example, if we want to calculate the "cradle-to-gate" emissions for an XPS implementation on a single dwelling building pre-1960 we have:

$$3{,}14 kgCO2eq/m^{\wedge}2 * 21.1m^{\wedge}2 * 4 = 265{,}02\ kgCO2eq$$

This procedure was done for each type of building and era resulting in 44 constructive measures of XPS, EPS and PVC-double glazed windows.

110 mm EPS Insulation

The Expanded Polystyrene foam is known for its tough, strong, light weight and rigid thermoplastic insulation foam, whose density varies from 18 to 22 kg/m^3 [49]. Concerning this environmental product declaration where the impacts of $1m^2$ of EPS, with a thermal conductivity of 0.031W/(m.K) were explained, we performed the same procedure done in the XPS insulation, resulting in a "cradle-to-gate" impact of 67.07 $kgCO2_{eq}$ and an end of life stage impact of 33.63 $kgCO2_{eq}$ where 100% of this product is processed and incinerated [45].

PVC frame double-glazed window

This type of building material for window frames has a low impact during the manufacturing phase, when compared to aluminum for example [50]. Calculating its lifecycle impact and considering an area of 1.82m^2 per window, we have 118.778 kgCo2$_{eq}$ for the "cradle-to-gate" phase. The end of life stage represented 10.688 kgCO2$_{eq}$ considering the materials that cannot be recycled.

It is also important to notice that the lifecycle performance of each measure, beyond the emissions of each period of its lifetime, was also assessed considering its cost and energy savings. Consequently, the Portuguese electricity mix during the year of 2019 needed to be considered, as well as the emissions factors of 2017, which are detailed in the Table 3.5 ([51], [52]):

Table 3.5 - Portuguese electricity mix with GWP potential and Emissions adapted from [45]

Energy Source	Contribution to Production	GWP Emission Factor (kgCO$_{2EQ}$/kWh)	Emissions (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
TOTAL	100%	2.46	0.30

For the end of life stage of the equipment, we considered the hypothesis of the materials being recycled. Therefore, given the Portuguese recycling rates, we have attributed a rate of 29% for the constructive measures and a 44% for the technological measures [53].

Furthermore, 6 technological measures were considered – see Table 3.6. On the technological measure No 45, 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 for the LED illumination while the Compact Fluorescent Lamps (CFL) only have 10,000 of operating time . For measure No 46 the average operating lifetime for the LED technology is 25,000 hours while the halogen lamp has only 2,000 hours.

Table 3.6 - Technological Measures adapted from [45]

Measure	Old Technology Lifecycle Impact	New Technology Lifecycle Impact	Reference
45: Replacement of CFL (Compact Fluorescent Lamp) (62W) with LED (23.2W)	0.0482 $kgCO_{2eq}/m^2$	0.134 $kgCO_{2eq}/m^2$	[54]
46: Replacement of Halogen Lamps(42W) with LED (8W)	0.3285 $kgCO_{2eq}$	2.4 $kgCO_{2eq}$	[55]
47: Replacement of Domestic Electric Storage Water Heater with Solar Heater with Electric Backup with a 150 litres capacity	-	21.403 $kgCO_{2eq}$	[56]
48: Replacement of Natural Gas boiler with a Heat Pump (5kW)	0.220 $kgCO_{2eq}/kWh$	0.276 $kgCO_{2eq}/kWh$	[57]
49: Replacement of Natural Gas Boiler with Biomass Boiler (Pellets)	0.220 $kgCO_{2eq}/kWh$	21.664 $kgCO_{2eq}$	[58]
50: Replacement of Domestic Electric Storage Water heater (2kW) with a Heat Pump (5kW)	-	0.276 $kgCO_{2eq}/kWh$	[59]

The performance of each measure is detailed in Annex A.1.

3.1 Indicators

We have considered as indicators the SIR, the CPBT, the CCE and a risk associated with each measure. The performance of each measure is detailed in the following sub-sections.

3.1.1 Savings to Investment Ratio

The SIR indicator is used to determine if the potential savings of a project sustains the initial investment. It is a very useful indicator for energy-efficient measures as it helps to determine if, for example, the savings of the instalment of a more energy efficient technology justifies the cost of replacing the existing one. Hence, it makes this indicator extremely useful when it is necessary to decide between two different design options [60]. In order to calculate this indicator, we need to consider a discount rate *d*. We chose the discount rate of 5% based on the same rate used in PPEC 2017/2018, and the formula is given as [61]:

$$SIR = \frac{\sum_{t=1}^{T} \frac{Annual\ Energy\ Savings}{(1+d)^t}}{Initial\ Invesment} \tag{3.2}$$

where T is the lifespan of the equipment.

3.1.2 Carbon Payback Time

The CPBT indicator considers the GHG emissions in CO2 equivalent and helps to calculate the time it would take for the avoided emissions when implementing a measure, to equal the emissions generated by its manufacturing and disposal, per years [45]. The formula goes by:

$$CPBT = \frac{Cradle\ to\ Gate\ Emissions\ (\mathrm{kgCO2eq}) + End\ of\ Life\ Emissions\ (\mathrm{kgCO2eq})}{Annual\ Avoided\ Emissions\ (\mathrm{kgCO2eq})} \tag{3.3}$$

3.1.3 Cost of Conserved Energy

The CCE is an economic indicator which estimates the avoided energy cost. It is the ratio between the difference of the financial cost and the difference of consumption when we are comparing two different technologies. Hence, it can be interpreted as the avoided energy cost. Hence, if the $/kWh is inferior to the current energy price, then the investment under analysis is viable. The formula is given as [62]:

$$CCE = \frac{Investment}{Annual\ Energy\ Savings} \times \frac{d}{1-(1+d)^{-n}} \tag{3.4}$$

Where *d* is the discount rate used in PPEC 2017-2018 and *n* is the lifespan of the measure.

3.1.4 Risk

We have used the results of a questionnaire conducted with several energy experts concerning the risks of adopting certain energy efficiency measures, in the framework of the T4ENERTEC project. Then, we obtained a risk factor through the use of TOPSIS [63]. This risk factor considers several good or bad aspects inherent to the measures under analysis. The experts assigned a score of 1-5 to each aspect linked to each type of measure. Table 3.7 provides an overview of the mean scores assigned by the experts to each measure. Each value assigned to each aspect under analysis is given by Xij, with rows i= 1…6 and columns j = 1….8.

Table 3.7 - Mean value results obtained from questionnaire

	A8	**A7**	**A6**	**A5**	**A4**	**A3**	**A2**	**A1**
PVC	2.83	1.82	2.58	3.17	3.42	1.58	3.67	4.58
XPS.EPS	1.67	1.64	2.83	2.83	2.42	1.58	3.5	4.33
LED	3.67	3.67	1.17	4.58	4.75	3	4.33	3.33
Solar Heater	2.5	2.91	3	3.58	3.08	2.33	4.58	4.25
Pumps	3	4	2.75	3.67	2.92	2.83	4.33	3.92
Boiler	2.67	2.73	2.42	3.33	2.75	2.58	4.42	4.08

Table 3.8 provides a description of the aspects considered by the experts.

Table 3.8 - Description of the aspects

#	**What is?**	**Good or bad?**	#	**What is?**	**Good or bad?**
A8	Susceptibility to behavioural factors	Bad	**A4**	Ability to penetrate the market in the absence of incentives	Good
A7	Potential to participate in the process of flexibility creation	Good	**A3**	Risk of generating a rebound effect	Bad
A6	Application difficulties due to the lack of trained labour	Bad	**A2**	Potential to contribute to the objectives from NECP	Good
A5	Relative importance of energy efficiency in consumer decision making in the absence of incentives	Good	**A1**	Suitability to be supported by energy efficiency public promotion policies	Good

Then, a “weight” (Wij) was assigned to each aspect (Aj, j = 1…8). Although the weights used can be subjective, in our work, we gave the same weight to all aspects.

The first step was to calculate a normalized matrix using $\overline{Xij} = \frac{Xij}{\sqrt{\sum_{j=1}^{n} Xij^2}}$ .Then, we weighted each result according to the weight given to each aspect of the risk $Vij = \overline{Xij} \times Wij$ resulting in a table with Vij.

The third step was to calculate the ideal best and worst value, meaning that the minimal value of a bad aspect corresponds to the ideal best and its biggest value corresponds to the ideal worst. Afterwards the next step consists of calculating the Euclidean distance of each Vij to the ideal best and to the ideal worst, mathematically: $Si^+ = \left[\sum_{j=1}^{m} (Vij - Vj^+)^2\right]^{0.5}$and $Si^- = \left[\sum_{j=1}^{m} (Vij - Vj^-)^2\right]^{0.5}$. Where *m* is the maximum number of aspects, in this case 8.

Finally a performance score is calculated through the following expression: $Pi = \frac{Si^+}{Si^+ + Si^-}$; where we we obtained the final ranking values, which are detailed in the following table:

Table 3.9 – Risk ranking of each type of measure

Type of Measure	Performance	Rank
PVC	0,59104999	5
XPS, EPS	0,587136269	4
LED	0,425794403	1
Solar Heater	0,575790918	3
Heat Pumps	0,550518003	2
Boiler	0,62085443	6

The results were not surprising as the LED replacement measures had the least risk factor meaning a higher rank in our scale [64].

4 Methodology

In this section, a brief explanation of the mathematical model proposed will be presented. Then, we also describe the genetic algorithm used to evaluate and select portfolios consisting of energy efficient measures, which is based on NSGA-II proposed in [65].

4.1 Mathematical Model Implementation

Based on the indicators that were exposed in Section 3.1 we have obtained the five objective functions and five constraints.

4.1.1 Objective Functions

The objective functions are not computationally heavy, an important issue in the performance of genetic algorithms [66]. As the algorithm is set on the foundations of the NSGA-II, this tool is programmed to optimize the problem towards the minimization of the objective function. Hence, an objective function being maximized is converted into an objective function being minimized just by considering its symmetrical value. In the following objectives, x_i is the decision variable which represent the number of interventions of each measure $i = 1 \dots n$, where $n = 50$. $Cost$ is the investment of each measure and $Budget$ is the capital allocated for the residential sector measures, which in our case was 3 000 000 €, based on the PPEC's budget attribution to the residential sector [19]. Hence, the objectives to be considered are:

- ➔ Maximize the SIR, in order to get back the investment in the implementation of the portfolio.

$$f_1 = min \sum_{i=1}^{n} -(SIR_i \cdot x_i) \qquad (4.1)$$

- ➔ Minimize the CPBT, in order to maximize the reduction of GHG emissions therefore maximizing the direct health benefits that this indicator carries, as explained earlier.

$$f_2 = min \sum_{i=1}^{n} CPBT_i \cdot x_i \qquad (4.2)$$

- ➔ Minimize the CCE, so we get the best possible economical outcome from a consumer point of view, maximizing savings to the consumer and consequently extracted the best direct economic benefits this objective can produce.

$$f_3 = min \sum_{i=1}^{n} CCE_i \cdot x_i \qquad (4.3)$$

- ➔ Minimize the risk indicator, in order to stakeholders, businesses or any other agent using this kind of implementation to be at ease regarding the risk aspects that each type of measure represents. This indicator is also a way of dealing with uncertainty, commonly done in this kind of multiple-objective problems.

$$f_4 = min \sum_{i=1}^{n} RISK_i \cdot x_i \tag{4.4}$$

- ➔ Minimize the distance to the portfolio budget, so we get the most from the proposed budget.

$$f_5 = min \sum_{i=1}^{n} |((Cost_i \cdot x_i) - Budget)| \tag{4.5}$$

4.1.2 Constraints

The upper and lower bounds, or in order words the maximum and minimum number of interventions for each measure are given as:

$$Upper\ bounds = \frac{Budget}{Cost_i} \cdot B = C_{1i} \geq x_i\ , i = 1 \ldots 50 \tag{4.6}$$

where B is the percentage of the $Budget$ that we want to assign to a certain type of measure. For our problem, we have based ourselves on PPEC 2017/2018 [19]. In this context, we have considered that 20% of the budget would be assigned to insulation measures, 32% to LED replacement measures, 11% to boiler replacement measures and 37% to Heat Pumps and Solar Heater related measures. This is done to guarantee a given level of diversification of the investment.

Lower bounds have been also imposed to account for the implementation of each measure at a reasonable level. For example, for LED replacement measures it is typical to have massive amounts of implementations, such as 100,000, so it doesn’t make sense to just consider a level of replacement of 10 or 100 lamps. Hence, for simplicity, we have decided to use as lower bounds 10% of the value considered for the upper bounds:

$$Custom\ lower\ bounds = 10\% \times C_{1i} = C_{2i} \leq x_i\ , i = 1 \ldots 50 \tag{4.7}$$

The final constraint refers to the maximum number of implementations per portfolio which must not be superior to the available budget:

$$Budget\ Contraint = \sum_{i=1}^{n} Cost_i \cdot x_i = C_{3i} \leq Budget\ , n = 50 \tag{4.8}$$

4.2 Genetic Algorithm

The introduction to Genetic Algorithms (GA's) herein given is based on [67].

The globally accepted concept that in living beings the ones that do not adapt to the environment have the greatest chance of not surviving is called natural selection. On the contrary, the most capable ones, the ones that evolve, live longer lives and reproduce, making it possible for their offspring to heir good qualities. The so called evolutionary algorithms are the computational version of this natural selection. One of these types of algorithms are the GA's, which won a big notoriety due to their simplicity and, most importantly, effectiveness.

Generally, any optimization task can be seen as a problem that we want to solve and can be described as a search within a possible solutions space. When this space is small, any algorithm that searches for the solutions in an exhaustive way is enough to find the wanted solution. However, if the space is big, this exhaustion methods don't work, and the Artificial Intelligence (AI) techniques are used. The GA's are examples of these type if techniques, being a bit different from most due to work with various alternative solutions simultaneously.

The GA's are techniques of stochastic optimization proposed by John Holland and inspired on the evolutionary process of natural selection suggested by Charles Darwin in its work *Origin of Species* and complemented by the genetic principles proposed by G. Mendel. GA's normally use a population of possible solutions for a given problem. The individuals of that population are chosen for reproduction where the fittest ones have higher probability of being selected more often. This reproduction normally consists of the trade of information between parents in a process known as recombination or crossover. These new generated individuals can be changed locally through an operator called mutation. So, through an iterative process and through various generations, the algorithm makes the population evolve.

```
How it works: 1 – Generation of initial population;
              2 – Until its_not_finished do
                  2.1 – Evaluation of the population;
                  2.2 – Selects parents for reproduction;
                  2.3 – Offspring are born through recombination;
```

```
        2.4 – Mutation is applied to offspring;
        2.5 – Substitutes old population with new one;
    End of Until;
    3 – Returns the final population solution;
```

This is how a GA works generally, but a series of methods of selection, recombination and mutation exist. The choice of this methods is crucial since it lets the GA explore globally through the search space and get closer to better regions.

In the context of this work, we will compare forms of these genetic operator and how they behave towards finding the solution to our problem. It is important to understand some nomenclature of GA's to go through the next sections:

- An **individual** represents one potential solution to the problem, in our case, one **portfolio**, which is formed by **genes** which are the different measures that an individual has (50), a group of genes forms a **chromosome**. The **alleles** are the information of each gene, meaning that they represent the number of implementations of each measure. Hence, the population is formed by a number of individuals, or a number of portfolios, each with a number of energy efficient measures and each measure has a number of implementations. As we have insulation measures (44), LED replacement measures(2), and the rest of the technological measures (4), our portfolios will then be consisted of 3 different chromosomes where each contains these group of measures, which will be useful to trade information in the recombination and mutation phases as we will see in the next few sections.

This is translated into a (population_size ,50 measures) matrix which is the total population that is constantly evolving through the generations.

4.2.1 Adjusted implementation based on NSGA-II (Non-dominating Sorting Genetic Algorithm)

The NSGA-II is a well-known multi-objective optimization algorithm that has some special features. More precisely, the fast non-dominated sorting approach and the fast crowded distance estimation procedure, which basically sets on a Pareto dominance relation where a rank is assigned to non-dominated individuals and then these individuals are removed from the current population. Then, another rank is assigned to the remaining non-dominated individuals and these are again removed, until all the population has an associated rank. The NSGA-II also incorporates its own genetic operators, more concretely a simulated binary recombination and a polynomial mutation ([68], [69]).

However, we have developed another type of selection, and our own genetic operators aiming to customize them to our own problem context.

4.2.1.1 Initial Population

The initial population was generated randomly but not entirely, as the randomness has to be bounded by upper and lower bounds. In our case it is a number of measure implementations, so it needs to be a vector of integers and this vector represents an individual, or in this context, a portfolio. Hence our population is represented in a matrix, with i individuals which are constituted by j genes:

$$\begin{bmatrix} x_{1,1} & \cdots & x_{1,j} \\ \vdots & \ddots & \vdots \\ x_{i,1} & \cdots & x_{i,j} \end{bmatrix}$$

4.2.1.2 Roulette Selection

This method is based on the attributed value to each individual by the evaluation function, the so called fitness. According to the quality of each individual, a portion of the roulette is given to each one of them, so the probability of an individual being selected depends solely on its quality. The roulette is spun i times, which corresponds to the size of the population, stopping in one of the individuals. At the end of i spins we have selected the parents that will breed the next generation.

So, after this, the algorithm simulates a wheel which selects the parents for the next generation, ordering them by the best fitness.

4.2.1.3 Sectioned Crossover

Every pair of individuals has a different chance to be selected for reproduction, hence the recombination operator grabs two parents which are selected iteratively and trades their genetic information breeding new individuals with new characteristics. In this specific case, a random gene is selected and if the gene belongs to a specific chromosome all the information corresponding to that chromosome is traded and the rest is maintained, generating two new individuals. In other words, we had three chromosomes that corresponded to each type of measure, one for the insulation measures, another for the LED measures, and the final one for the technological measures. This division was done due to the diversion of the number of implementations that each type of measure had. Hence, in a simple way:

```
parent1 and 2 is selected;
k = random gene from 1:50;
    if k = LED measures
        son1= [genes from dad1, LED genes from dad2, genes from dad1];
        son2= [genes from dad2, LED genes from dad1, genes from dad2];
```

Exemplifying for the LED measures. This is done iteratively until the new population is formed, meaning that dad1 and dad2 are chosen 25 times if the population has 50 individuals.

4.2.1.4 Adjusted Mutation

A mutation is a modification of the genetic information within a gene. It applies to all genes meaning that every gene has a probability of being mutated. Even though this genetic operator is sometimes considered to be a secondary operator when compared to the recombination, it still plays an important role in a GA. It helps the algorithm to avoid stagnation in a local maximum by jiggling it and making it search for other regions. In our concrete case, the adjusted mutation operator increases or decreases the number of implementations (gene information) of a measure (gene) chosen randomly, according to the distance to the budget. In other words, if this distance is within a certain value or over zero (over the budget) the number of implementations of a measure is correspondingly increased or decreased. Another important aspect is that the probability of this mutation occurring is increasingly lower as the generations increase since it is assumed that with the development of the population, its quality will theoretically raise and therefore be less prone to mutations. Also, if a certain number of generations has passed, the distance to the budget is reduced as well as the number of implementations to be applied or removed. Generically we have:

```
For index = 1 to pop;
distance = excel read;
```

```
implementations = excel read;
k = random gene 1:50;
    if k = insulation measures
        t = random gene 1:44
        if fit(index, 5) < -distance
mutatedson=[son (index,1:(t-1)), (son(index,t) + implementations), son(index, (t+1:50)) ]
        if fit(index, 5) > 0
mutatedson=[son (index,1:(t-1)), (son(index,t) - implementations), son(index, (t+1:50)) ]
        if fit(index,5) < 0 && fit(index,5) > -distance
mutatedson = son(index,:)
```

Exemplifying for the insulation measures. This is done iteratively until the new population is formed, as every individual has a different chance of being mutated. This probability is checked outside of the function, in main.

4.2.1.5 Stopping Criteria

Normally, for simple GA's, there is three different kinds of stopping criteria that can be employed: a pre-defined number of generations is reached – the most common criteria- , another where a computation time limit is reached, and at last the chance of achieving significant changes in the next generations is low enough to a stage where doing more generations is pointless [70]. In our work we followed the criteria done in the NSGA where the condition of a maximum number of generations is met.

5. Results

For the application of the presented model the software MATLAB version 2019a was used since it is relatively easy to use and the NSGA-II tool has already been implemented and optimized in MATLAB as well. After understanding and running a few tests on the software, each objective function and constraints described on the fourth chapter was programmed. Regarding the actual structure of the whole program, the original provided software was heavily changed, as new genetic operators, menus, excel reads, constraints impositions, population number and tweaks to elaborate this NSGA-II based implementation were introduced.

The program starts by reading from an excel file the indicators that characterize each measure, the upper and lower bounds and the parameters that the users wish to use. These are the budget, the number of generations, population size and the mutation parameters. After reading all the necessary parameters the population is generated randomly within the stipulated boundaries and then the evolutionary process starts until the stopping criteria is met (maximum number of generations). The main characteristic of the NSGA-II used in this work was its concept and philosophy such as its non-dominant sorting approach to generate Pareto fronts, which was tweaked to support five objectives, as the original NSGA-II only produces fronts considering two objectives.

A critical step in GA's is the identification of an adequate set of parameters required by the algorithm. The final parameterization was selected after a trial and error process in which several runs of the GA were done. Parameters are: 500 individuals; 5000 generations; a crossover probability of 0.65, and a mutation probability of 0.001, which resulted in a run time of approximately 30 minutes.

In the following sections several results will be analyzed. Namely, a comparative analysis of results obtained using the original operators implementation and the results obtained with the operators hybrid implementation developed in this work is carried out. In order to be able to compare the results encoded in a potential solution identified by the GA with the energy efficiency actions funded in the framework of the PPEC program an implementation of a mathematical model with only two objective functions has also been done.

5.1 Original NSGA-II vs Adjusted Implementation

The first analysis consisted of contrasting the original NSGA-II with our adjusted implementation of the algorithm. So, after one run, the best individuals for each objective that fully respect the constraints are analysed and compared – see Tables 5.1 and 5.2.

Table 5.1 - Original NSGA-II Performance

	SIR	**CPBT**	**CCE**	**Risk**	**Distance to Budget**
Best individual concerning SIR and Distance(0.0095)	7 557 751	115 390	1 181	134 808	123 973
Best individual concerning CPBT and Risk(0.0181)	634 320	17 943	2 880	17 972	545 841
Best individual concerning CCE(0.0801)	6 349 262	94 006	127	111 398	956 368

Table 5.2 - Adjusted implementation Performance

	SIR	**CPBT**	**CCE**	**Risk**	**Distance to Budget**
Best individual concerning SIR(0.080)	6 158 096	109 155	137	108 223	177 482
Best individual concerning CPBT(0.0026)	583 231	2 429	2 162	15 826	815 966
Best individual concerning CCE(0.0032)	6 151 501	89 785	99	108 085	657 421
Best individual concerning Risk(0.0274)	426 450	26 097	1 650	11 545	289 728
Best individual concerning Distance(0.0079)	6 133 882	98 990	217	109 145	6 073

From the analysis of Tables 5.1 and 5.2 it is possible to conclude that the original NSGA-II had a better overall SIR performance throughout all the best individuals for each objective. However, when considering the best individuals for the rest of the objectives, the adjusted implementation had a better performance in this run. To compare the performances of both algorithms Table 5.3 was built, where O means the original NSGA-II was better, and C means that the adjusted implementation had a better performance.

Table 5.3 – Comparison between performances

	SIR	CPBT	CCE	Risk	Distance to Budget
Best individual concerning SIR	O	C	C	C	O
Best individual concerning CPBT	O	C	C	C	O
Best individual concerning CCE	O	C	C	C	C
Best individual concerning Risk	O	O	C	C	C
Best individual concerning Distance	O	C	C	C	C

From the observation of Table 5.3 we can see that it has more C's than O's, and the C's are more valuable because they win in the objectives that are supposed to be better for that individual. In other words, the adjusted implementation got better values for CPBT when CPBT was meant to be the better, and that also happened for the CCE, risk and distance for each of their best individuals.

However it is still early to reach any conclusion because it is also important to inspect these algorithms in other ways such as how many non-dominated solutions are obtained in the 500 individuals, how many are feasible (respected the constraints) and the variety of solutions.

First, the adjusted algorithm had 215 non-dominated solutions from the 500 and the original had 196 from the 500. Considering feasible solutions, about half of the solutions were infeasible in the original NSGA-II because the algorithm simply did not respect the adapted lower bound constraint. However, in the adjusted implementation this was not the case as only about 10 solutions did not respect it.

Tables 5.4 and 5.5 contrast the algorithms in terms of the variety of the solutions obtained, where the numbers between brackets correspond to the number of the measures and implementations, respectively, and each table corresponds to its version of the algorithm.

Table 5.4 - Measures chosen by the algorithms

Solutions	Constructive measures (which, how many)	LED measures	Technological measures
Best SIR and Distance (O)	(1, 634), (7, 155) , (9, 596), (12, 41), (18, 82), (21, 225), (24, 156), (31, 589), (43, 355)	(46, 297 320), (45, 15 375)	-
Best CPBT and Risk (O)	(7, 165) , (9, 557), (12, 38), (21, 256), (24, 192), (31, 541), (43, 409), (44, 242)	(45, 38 898)	-
Best CCE (O)	(1, 289) , (3, 522) , (5, 235), (9, 218), (39, 278) , (42, 81)	(46, 258 629)	(50, 679)

Table 5.5 - Measures chosen by the algorithms

Solutions	Constructive measures (which, how many)	LED measures	Technological measures
Best SIR (C)	(2 , 98), (5, 1067), (17, 965), (26, 968), (31, 233), (34, 225)	(46, 248 920)	(49, 238)
Best CPBT (C)	(5, 1067), (17, 824), (26, 544), (31, 233)	(45, 32 726)	(48, 685)
Best Risk (C)	(2, 98), (5, 1066), (26, 968), (31, 233), (34, 225), (44, 167)	(45, 21 635)	(49, 239)
Best Distance (C)	(3, 241), (27, 73), (30, 152), (33, 2991), (40, 405), (43, 897)	(46, 248 920)	(47, 502), (48, 178)

From Tables 5.4 and 5.5 it is possible to see that the original NSGA-II used less technological measures while it used more variety in the constructive measures. Hence, in terms of variety both algorithms are balanced. One important aspect is that we can conclude that LED replacement measures are by far the best across all objectives, as they excel not only in the use phase favouring the SIR and CCE indicators, but also in the cradle-to-gate and end of life emissions, favouring the CPBT indicator.

The last factor is the run time of each algorithm which was similar, as the original NSGA-II ran for about 31 minutes and 25 seconds and our adapted one had 30 minutes and 43 seconds.

Concluding this first analysis, it seems that both algorithms have their own utility, because on one hand the original NSGA-II has a better SIR performance for this one specific run but it lacks of non-dominated solutions and is worse on the rest of the objectives. On the other hand, the adjusted implementation has a better overall performance, has more non dominated solutions and a better run time.

However, a statistical analysis (running a lot of simulations and compare the results) needs to be performed in order to take any further conclusions about which algorithm is in fact better. Therefore, the conclusions given here are only for this specific run and need to be approached with care.

5.2 Five objective approach vs two objective approach

In this subsection, the approach that we used on the previous section will be compared to another implementation consisting of only two objectives (SIR maximization and risk minimization, but prioritizing SIR), in order to compare its results to the results PPEC has. In this implementation of the model with only two objectives the parameters are the same as previously defined. Hence the purpose of this analysis is to observe the differences when the optimization procedure takes into consideration a more broad approach, considering multiple objectives which also consider the lifecycle of the implemented measures, and a more narrow approach, considering only two of the objectives: SIR maximization and risk minimization. The latter approach being closer to the one used in PPEC. For this, the number of implementations of each measure in each portfolio will be compared to study the intensity and diversity of each portfolio in each approach.

Tables 5.6 and 5.7 provide information regarding the connection between the measures identified by the GA and PPEC’s proposed measures.

Table 5.6 – Information about PPEC's proposed measures [19]

	PPEC Cost (€)	Implementations	Budget Percentage
LED's	994 337	200 000	33.3%
Efficient Water Heater	247 500	1 500	8.3%
Heat Pumps	1 139 133	1 800	38%
Constructive measures	611 233	1 200	20,4%
TOTAL	**2 992 203**	**204 500**	**100%**

Table 5.7 – Best individual from two objective approach simulation

	Constructive measures	LED	Technological
Measures	(12 ,45), (17, 2363), (19,95), (20, 587), (24,252), (36, 560), (42, 268)	(46, 141 084)	(47, 487), (50, 391)
Total implementations	4170	141 084	878
Cost (total = 2 572 938 €)	1 643 075 €	458 523€	476 214€

The main differences between these two tables is the bigger investment in the constructive measures by the algorithm and the decreased investment in LED and technological measures. The results from the algorithm run may be justified, because the constructive measures (measure 17 to be precise) have a slightly better SIR then the LED measures and the technological measures, since the use phase and the corresponding energy savings are higher. Another difference is that the algorithm still had more than 400 000 € to use, so the remaining budget could be used to increase implementations and therefore increasing performance. This comparison is to validate the next comparison between the algorithms with two different approaches:

Table 5.8 provides information on the performance of the indicators for the best individuals.

Table 5.8 – Performance of the indicators of both approaches

	SIR	CPBT	CCE	Risk	Distance to Budget
Best individual concerning 2 objectives	3 800 995	-	-	68 514	-
Best individual concerning 5 objectives	6 158 096	109 155	137	108 223	177 482

From Table 5.8 it is possible to conclude that while considering five objectives at the same time and prioritizing the SIR indicator the algorithm still had a better performance than only with the SIR and risk. This is also due to considering the CCE and the distance to the budget, because the measures with a good CCE also have a good SIR, and the algorithm uses more implementations due to the minimization of the distance to the budget.

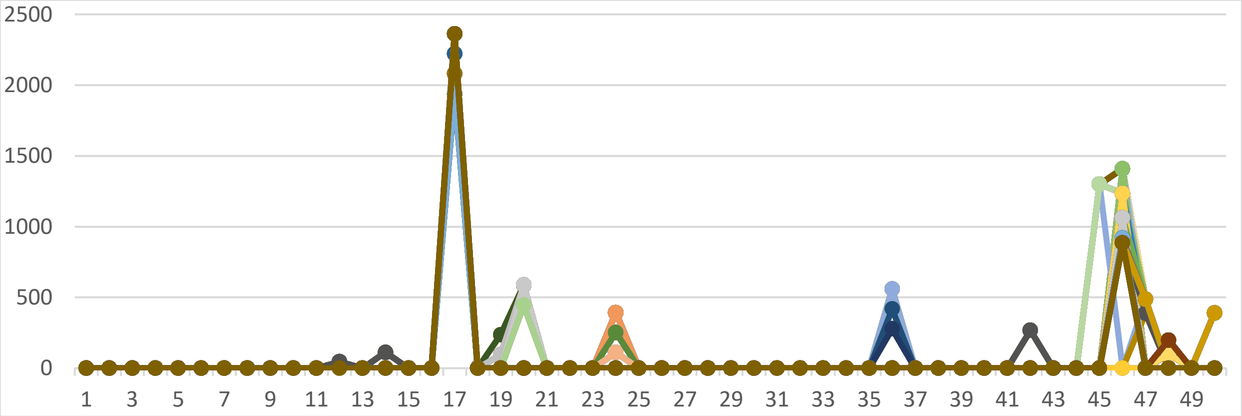

Figure 5.1 – Chart of the number of implementations considering a two objective approach

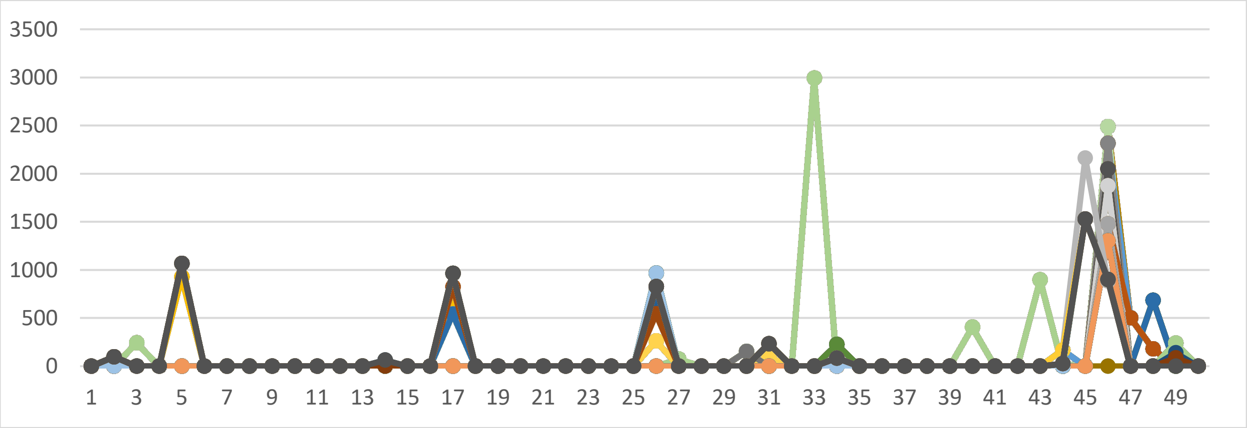

Figure 5.2 – Chart of the number of implementations considering a five objective approach

First of all, related to Figures 5.1 and 5.2 where they represent the number of implementations of each measure of each portfolio for the two objective and five objective approach respectively, the number of implementations of the LED measures (measures 45 and 46) are divided by a factor of 10 and 100 respectively for observation purposes, so clearly the LED measures is the big winner. Another consideration is that the population was ordered and chosen by the “best” individuals regarding the SIR indicator, because it is hard and redundant to show 500 individuals at the same time. With this representation it is possible to get a grasp of the main differences between both approaches. It is visible that in terms of diversity the traditional approach tends to select constructive measures, particularly measure 17 which is the XPS insulations on buildings prior to 1960. This happens because these measures have a higher impact when only considering the SIR and the risk indicators. As the SIR only considers the use phase, these measures are the best in terms of energy savings. However, considering the five objectives, the CPBT for example will need to take into account the rest of the LCA parameters which explains the tendency to go with measures 33, 26, 17 and 5 which have very little impact on the cradle-to-gate and end of life emissions, but it’s energy and carbon savings during the use phase are not so good so that is why it is not included in a traditional approach. The only similarities are the LED measures, as they excel both in energy savings and LCA parameters. It is also important to keep in mind that with a five-objective approach, we have more options when it comes to solutions for different types of strategies. Meaning that if the desired objectives to be favored are, for example, the CPBT and the distance to the budget we have a certain solution, and if the objectives prioritized are the SIR and Risk we have other solutions. Therefore, it is clear that an approach that considers multiple and different objectives that incorporates the LCA parameters is essential for selecting the best measures that meet the expectations of an energy policy that prioritizes objectives that are environmentally oriented.

Concluding this chapter, it is clear that it is not only important but necessary to take a multiple objective approach that considers a full lifecycle approach to reach goals set by decision-makers that focus on environmental and economic objectives. One last aspect is that the multiple benefits that are possible to obtain with energy efficient measures are intrinsically connected with these environmental and economic indicators. Therefore, this is one more big reason to favor a multiple objective approach in energy efficiency promotion programs.

5.3 Impact on different Strategies

On this chapter some of the non-dominated solutions will be further assessed when considering different types of objectives at the same time. As we know by now, it is not possible to find a “better” solution for five objectives at the same time, therefore the decision-maker just needs to select a non-dominated solution according to his/her own preferences. It is important to understand that a genetic algorithm has a heuristic and stochastic nature, meaning that the given results are an approximation of the optimal solutions and have a random feature attached to it (that comes from the initial population generation and the genetic operators), therefore it is only guaranteed that the best set of solutions is returned when the stopping criteria is met. Hence, in this particular analysis, the set of non-dominated solutions in the minimization of 2 or 3 objectives at the same time (while still considering the original five objectives) will be studied. However, this set might not belong to the final real Pareto set that the model returns.

Within the non-dominated solutions, it was thought to see how the objectives relate to each other, so the objectives were normalized. To normalize we used the maximum value for every objective and used it as denominator for every value. As the CPBT, CCE, Risk and the distance to the budget are to minimize, we had to use their complement (1 – new value = normalized value) for these new values. After this normalization, the individuals with SIR values within 0.7-1 were grouped - see Figure 5.4, and the individuals with CPBT values within 0.7-1 were also grouped - see Figure 5.5.

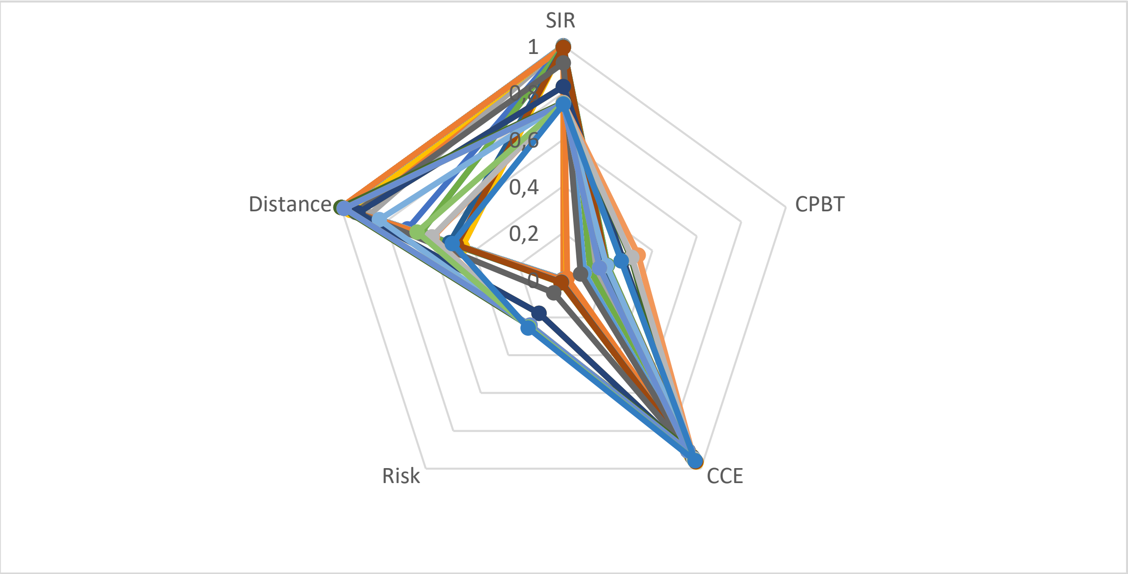

Figure 5.3 – Relationship between objectives when considering a SIR from 0.7-1

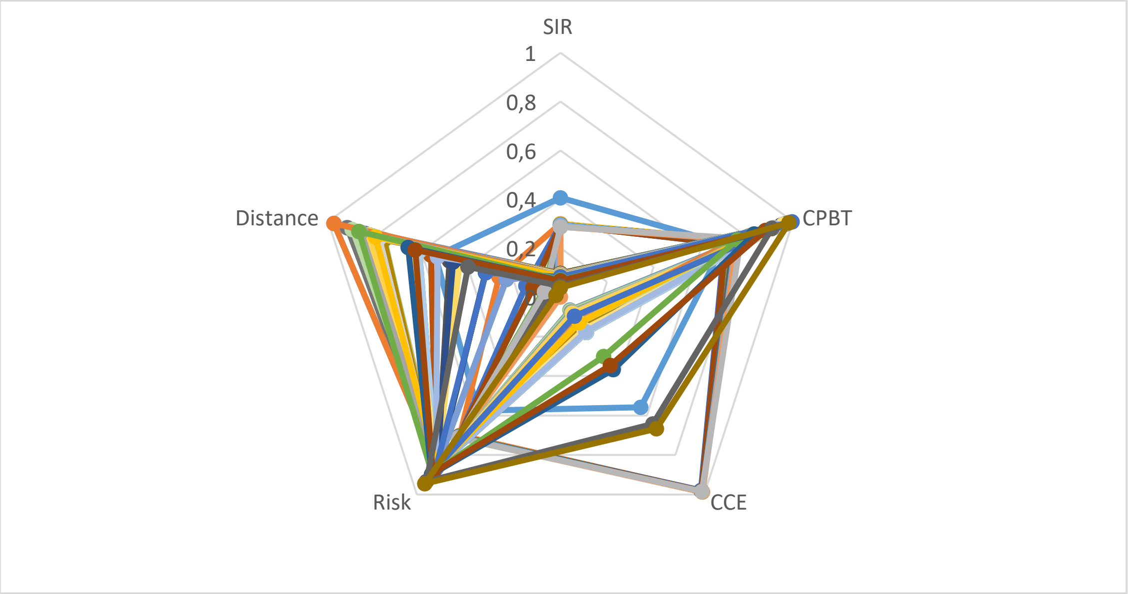

Figure 5.4 – Relationship between objectives when considering a CPBT of 0.7-1

From Figure 5.3 it is clear that the SIR, the CCE and the distance to the budget have a very strong relationship, while Figure 5.4 shows that the CPBT and Risk also are related to each other.

However, the purpose of this analysis is to explore the trade-offs between the objective functions. Hence, Figures 5.5 and 5.6 are meant to find the solutions with a SIR and CPBT within 0.4-0.6.

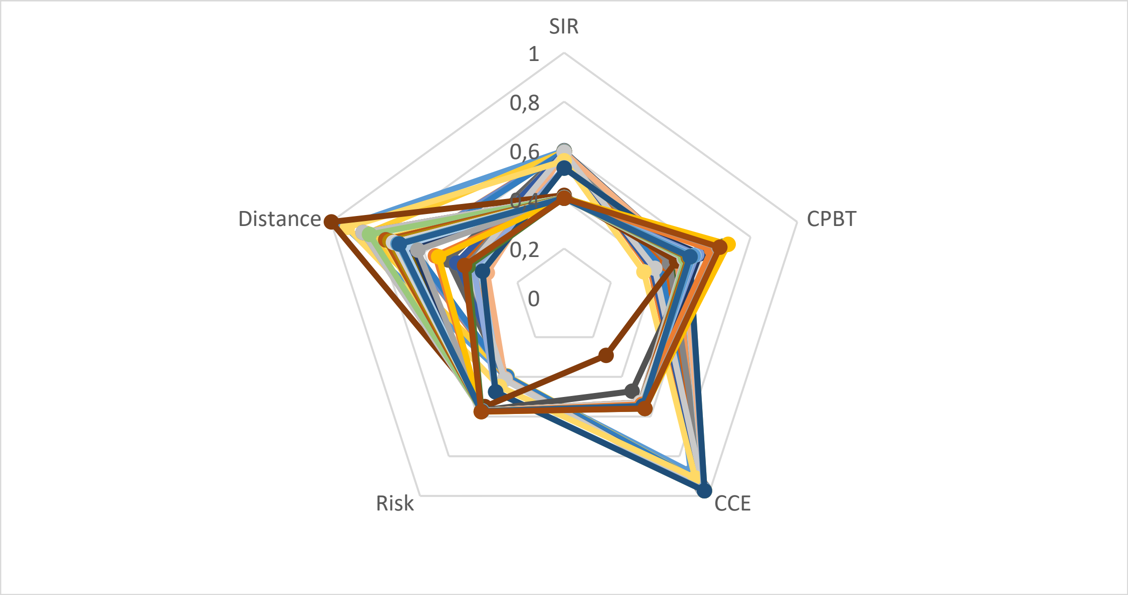

Figure 5.5 – Relationship between objectives when considering a SIR of 0.4-0.6

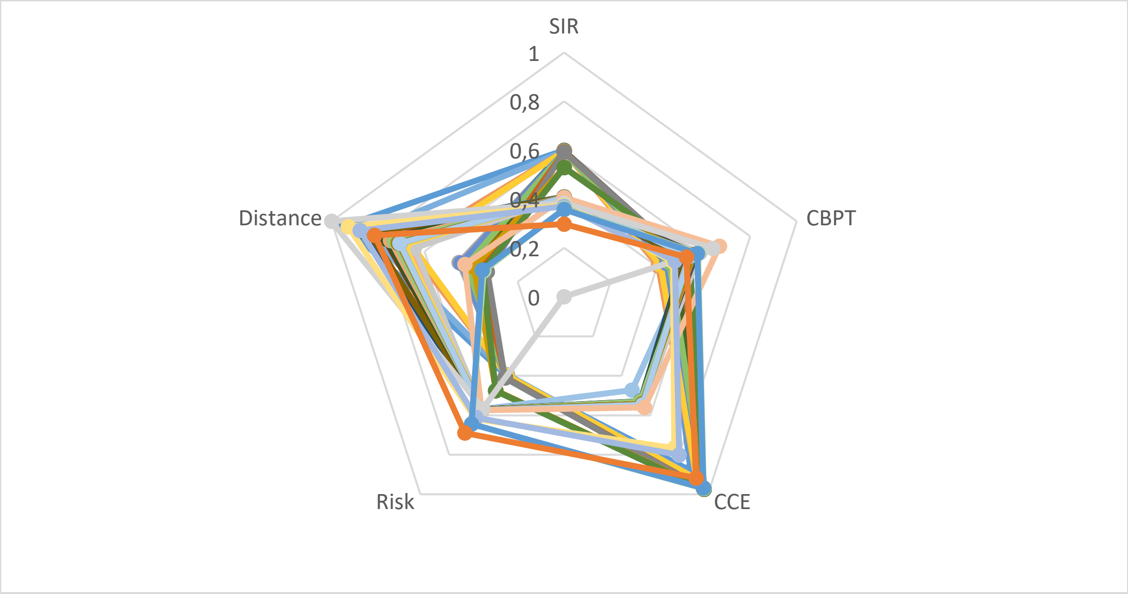

Figure 5.6 – Relationship between objectives when considering a CPBT of 0.4-0.6

We have selected a solution with balanced values across all objectives and we have compared it with the corresponding individual best solutions considering the SIR and CPBT, respectively – see Table 5.9.

Table 5.9 – Performance Comparison between the best SIR and CPBT and a solution with balanced values across all objectives

	SIR	CPBT	CCE	RISK	Distance to Budget
Balanced solution	3 259 685	50 327	60	57 206	1 425 102
Best SIR	6 158 096	109 155	137	108 223	177 482
Best CPBT	583 231	2 429	2 162	15 826	815 966

The chosen measures for these solutions are depicted in Table 5.10

Table 5.10 – Measures and implementations of the individuals from table 5.9

Solutions	Constructive measures (which, how many)	LED measures	Technological measures
Balanced solution	(2, 98), (5, 1067), (17,965), (26, 685), (34, 86)	(46, 130 354)	-
Best SIR	(2 , 98), (5, 1067), (17, 965), (26, 968), (31, 233), (34, 225)	(46, 248 920)	(49, 238)
Best CPBT	(5, 1067), (17, 824), (26, 544), (31, 233)	(45, 32 726)	(48, 685)

As it is possible to see, many of the selected measures across the three analyzed individuals are the same, meaning that the algorithm evolved with measures number 5, 17 and 26 (35mm XPS wall insulation on single and multi-dwelling buildings from 1961-1990 and prior to 1960 and after 2013), as they have a good balance between SIR and CPBT. The main differences are mostly in the chosen LEDs since measure 45 is better considering a CPBT oriented analysis and measure 46 is better from a SIR point of view. On the technological measures, the 5kW Heat pump was chosen because of its CPBT value (close to zero) and the biomass boiler was chosen for the best SIR due to its high energy savings.

6 Conclusion

Energy efficiency is becoming a big priority to most EU countries because it provides a cost-effective means for, among other benefits, reducing environmental impacts.

As a result, the EU Directive established that each Member State had to propose a national plan that met the goals established by the EU when it comes to energy efficiency and avoided energy and GHG emissions. Hence, it becomes relevant to study and develop new and innovative ways to assess energy efficient measures that are promoted by a national energy plan. On top of this, there is a lot of undiscovered potential when it comes to the multiple benefits that energy efficiency can bring.

Thus, it became pertinent to use a multiple objective optimization model to evaluate if these multiple benefits could be incorporated in such models and how heuristic and stochastic methods would behave. In this way, it was necessary to simultaneously analyse five objectives: the maximization of the SIR, the minimization of the CPBT, the CCE and of a risk measure inherent to the adoption of measures under analysis and the distance to budget. As such a literature review was conducted in order to understand the kind of multiple benefits that could be assessed and what kind of objectives and constraints were being used. After that analysis a multi-objective mathematical model was built, and a genetic algorithm was then used – an adapted NSGA-II – for searching non-dominated solutions.

After building the multi-objective problem and the energy efficient measures to be scrutinized were selected, the NSGA-II was implemented in MATLAB with specific adaptations, more concretely on the genetic operators, regarding the searching and grouping of the non-dominated solutions, and on increasing the number of objectives from two to five. Subsequently, the parameters were chosen after several tries and, simulations were conducted.

The results obtained with both methodologies were contrasted and it seemed that both algorithms were useful, since the original one exceled in terms of the SIR indicator and the adjusted implementation exceled on the other indicators in one run. It is also relevant to look through a multiple benefits scope, as the adapted algorithm got better results for the indicators that directly benefit public health, the environment, and the energy sector. Then results were also compared with a simpler approach considering only two objectives, closer to the one used in programs, such as PPEC. Hence the algorithm only accounted for the SIR and risk indicators. It was then concluded that a multiple objective approach that considers a full lifecycle approach is essential to reach goals set by decision-makers that focus on environmental and economic objectives, since the solutions that prioritize the SIR and distance to budget are different than the ones selected that prioritize the CPBT and risk for example. The last results showed the differences between a solution with balanced values across all objectives and solutions with individual best values. Our findings suggest that a simple change in the number of implementations and measures considered could influence the performance of the solution.

Finally, it was possible to answer to the original research questions considered in this work. The first one was “To what extent will it be useful to consider other benefits when analysing portfolios of energy efficiency measures?”. Although it was not possible to use a direct indicator on winter morbidity, for example, it was still possible to use indicators that directly influenced this sort of benefits. Overall, it was possible to conclude that the adapted algorithm herein developed allowed obtaining better results for the indicators that directly benefit public health, the environment, and the energy sector.

The second question was “To what extent does the use of different approaches for assessing and selecting portfolios of energy efficiency measures lead to different results?”. The results from section 5.2 can begin to help answering this question as the solutions obtained for a model with just two objective functions that only takes into account the use phase are visibly different than the solutions found for a model with five objectives that consider the full life cycle performance of the measure.

6.1 Future work

Considering the future work of this investigation, it is relevant to continuously analyze how multiple benefits and a multi-objective approach influence the evaluation of energy efficiency measures. Also trying more parametrizations for the genetic algorithm would be interesting, or even build another genetic algorithm only to choose the best parameters for that run. Analyzing all the results and comparing them with each other would result in a robust decision aiding tool.

It would be interesting to apply the constraint 4.8 from section 4.1.2 on every generation and then instead of turning the number of implementations that did not respect the constraint to zero, use a penalty system in the fitness values.

Another promising analysis would be to evaluate how each portfolio would perform towards meeting the NECP’s reduction in the emissions goal. On pair with this possible analysis, after having a robust and effective tool to identify the portfolios, it would also be interesting to have a tool to select the portfolio that performs better for any given objective, for example the NECP's objectives.

Applying this model to other sectors would also be valuable as well as using other simulation software instead of MATLAB and compare the obtained results.

As a last note, it is important to remind that changes/improvements to the model structure will make it more complex, thus increasing the computational burden involved.

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8. Annexes

8.1 A.1

Table A.1 - LCA and characterization of the measures [45]

Measure	Technology	Initial Cost (€)	Cradle-to-gate emissions (kgCO2eq)	Reduction in use phase emissions (kgCO2eq/year)	End-of-life Emissions (kgCO2eq)	Use phase energy savings (GJ/year)	Lifetime (years)	Recycling Rate (%)	Reimbursement (%)	Upper Bound	Lower Bound	Lower Bound_A
1	XPS 35mm	461,67	265,02	1331,08	94,31	47,49	35,00	0,29	0,50	1299,00	0,00	130,00
2	EPS 110mm	3229,145	5660,71	1331,08	834,89	47,49	35,00	0,29	0,50	185,00	0,00	20,00
3	XPS 35mm	437,055	258,40	524,04	89,28	18,70	35,00	0,29	0,50	1372,00	0,00	135,00
4	PVC frame double-gazed window	1134	783,12	56,35	-46,77	1,87	40,00	0,29	0,50	529,00	0,00	52,00
5	XPS 35mm	509,805	301,41	269,90	104,15	9,63	35,00	0,29	0,50	1176,00	0,00	118,00
6	EPS 110mm	3565,83	6250,92	269,90	921,94	9,63	35,00	0,29	0,50	168,00	0,00	17,00

7	XPS 35mm	547	323,40	655,87	111,74	23,40	35,00	0,29	0,50	1096,00	0,00	110,00
8	PVC frame double-gazed window	1417,5	978,90	76,43	-58,46	2,73	40,00	0,29	0,50	423,00	0,00	42,00
9	XPS 35mm	435,41	257,43	230,51	88,95	8,22	35,00	0,29	0,50	1378,00	0,00	138,00
10	EPS 110mm	3045,495	5338,77	230,51	787,41	8,22	35,00	0,29	0,50	197,00	0,00	20,00
11	XPS 35mm	423,38	250,31	507,64	86,49	18,11	35,00	0,29	0,50	1417,00	0,00	141,00
12	PVC frame double-gazed window	2929,5	2023,06	157,96	-120,82	5,64	40,00	0,29	0,50	204,00	0,00	20,00
13	XPS 35mm	446,35	263,89	236,31	91,18	8,43	35,00	0,29	0,50	1344,00	0,00	134,00
14	EPS 110mm	3122,015	5472,91	236,31	807,19	8,43	35,00	0,29	0,50	192,00	0,00	20,00
15	XPS 35mm	2922,73	266,48	540,43	92,08	19,28	35,00	0,29	0,50	205,00	0,00	20,00
16	PVC frame double-gazed window	3118,5	2153,58	168,15	-128,61	6,00	40,00	0,29	0,50	192,00	0,00	19,00
17	XPS 35mm	125,81	74,38	362,74	25,70	12,94	35,00	0,29	0,50	4769,00	0,00	477,00

18	EPS 110mm	879,98	1542,61	362,74	227,52	12,94	35,00	0,29	0,50	681,00	0,00	68,00
19	PVC frame double-gazed window	931,77	643,46	43,08	-38,43	1,54	40,00	0,29	0,50	643,00	0,00	64,00
20	XPS 35mm	130,185	76,97	68,92	26,60	2,46	35,00	0,29	0,50	4608,00	0,00	460,00
21	EPS 110mm	910,59	1596,27	68,92	235,43	2,46	35,00	0,29	0,50	658,00	0,00	66,00
22	PVC frame double-gazed window	967,68	668,26	52,18	-39,91	1,86	40,00	0,29	0,50	620,00	0,00	62,00
23	XPS 35mm	141,125	83,44	74,71	28,83	2,67	35,00	0,29	0,50	4251,00	0,00	425,00
24	EPS 110mm	987,11	1730,41	74,71	255,21	2,67	35,00	0,29	0,50	607,00	0,00	61,00
25	PVC frame double-gazed window	1315,44	908,42	70,93	54,25	2,53	40,00	0,29	0,50	456,00	0,00	46,00
26	XPS 35mm	137,845	81,50	72,98	28,16	2,60	35,00	0,29	0,50	4352,00	0,00	435,00
27	EPS 110mm	964,15	1690,16	72,98	249,28	2,60	35,00	0,29	0,50	622,00	0,00	62,00
28	PVC frame double-	1581,93	1092,45	85,30	-65,24	3,04	40,00	0,29	0,50	379,00	0,00	38,00

	gazed window											
29	XPS 35mm	125,81	74,38	362,74	25,70	12,94	35,00	0,29	0,50	4769,00	0,00	477,00
30	EPS 110mm	879,98	1542,61	362,74	227,52	12,94	35,00	0,29	0,50	681,00	0,00	68,00
31	XPS 35mm	355,55	210,21	426,31	72,63	15,21	35,00	0,29	0,50	1687,00	0,00	169,00
32	PVC frame double-gazed window	931,77	643,46	43,08	-38,43	1,54	40,00	0,29	0,50	643,00	0,00	64,00
33	XPS 35mm	130,185	76,97	68,92	26,60	2,46	35,00	0,29	0,50	4608,00	0,00	461,00
34	EPS 110mm	910,59	1429,67	68,92	235,43	2,46	35,00	0,29	0,50	658,00	0,00	66,00
35	XPS 35mm	382,9	226,38	459,11	78,22	16,38	35,00	0,29	0,50	1566,00	0,00	157,00
36	PVC frame double-gazed window	967,68	668,37	50,24	-39,91	1,79	40,00	0,29	0,50	620,00	0,00	62,00
37	XPS 35mm	141,125	83,44	74,71	28,83	2,67	35,00	0,29	0,50	4251,00	0,00	425,00
38	EPS 110mm	987,11	1549,81	74,71	255,21	2,67	35,00	0,29	0,50	607,00	0,00	61,00
39	XPS 35mm	519,65	307,23	623,07	106,16	22,23	35,00	0,29	0,50	1154,00	0,00	116,00

40	PVC frame double-gazed window	1315,44	908,42	70,93	-54,25	2,53	40,00	0,29	0,50	456,00	0,00	46,00
41	XPS 35mm	137,845	81,50	72,98	28,16	2,60	35,00	0,29	0,50	4352,00	0,00	435,00
42	EPS 110mm	964,15	1690,16	72,98	249,28	2,60	35,00	0,29	0,50	622,00	0,00	62,00
43	XPS 35mm	574,35	339,57	688,66	117,33	24,57	35,00	0,29	0,50	1044,00	0,00	105,00
44	PVC frame double-gazed window	1581,93	1092,45	65,12	-65,24	2,32	40,00	0,29	0,50	379,00	0,00	38,00
45	LED	19,99	0,13	26,89	0,00	0,31	25,00	0,44	0,50	48624,00	0,00	4862,00
46	LED	3,25	2,40	6,96	0,00	0,08	25,00	0,44	0,50	299076,00	0,00	30000,00
47	Solar Heater with Electric Backup	499,5	308,83	288,80	0,00	3,29	20,00	0,44	0,50	660,00	0,00	66,00
48	Heat Pump	1058	1293,75	-1652,31	0,00	18,90	20,00	0,44	0,50	1049,00	0,00	105,00
49	Biomass Boiler	2570	160,32	2,73	0,00	10,51	15,00	0,44	0,50	431,00	0,00	43,00
50	Heat Pump	595,8	1293,75	615,40	0,00	7,00	20,00	0,44	0,50	1863,00	0,00	186,00