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A RETROFIT DECISION SUPPORT APPROACH FOR IMPROVING ENERGY EFFICIENCY AND INDOOR ENVIRONMENTAL QUALITY IN BUILDINGS

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A RETROFIT DECISION SUPPORT APPROACH FOR IMPROVING ENERGY EFFICIENCY AND INDOOR ENVIRONMENTAL QUALITY IN BUILDINGS

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Dedication

To my parents: Abdolreza & Parvin

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A retrofit decision support approach for improving energy efficiency and indoor environmental quality in buildings

Ehsan Asadi, Ph.D.

University of Coimbra, MIT-Portugal Program, 2013

Retrofitting of existing buildings offers significant opportunities for reducing global energy consumption and greenhouse gas emissions. This is being considered as one of the main approaches to achieve sustainability in the built environment at relatively low cost and high uptake rates. Although there are a wide range of retrofit technologies readily available, methods to identify the most suitable set of retrofit actions for particular projects are still a major technical challenge. Such methods can be categorized into two main approaches; models in which alternative retrofit actions are explicitly know *a priori* and models in which alternative retrofit actions are implicitly defined in the setting of an optimization model.

This thesis focuses on using modeling and optimization techniques to assess technology choices in the built environment. Firstly two multi-objective optimization models using a classical optimization technique, namely Tchebycheff technique are developed. The functionality of the proposed models is discussed through the application on a residential building. The results verify the practicability of the approaches and highlight potential problems that may arise. Afterward a multi-objective optimization model based on the Genetic Algorithm Integrating Neural Network (GAINN) approach is developed. The benefits of this approach with respect to the classical optimization models are its rapidity and computational efficiency. This model is used for the optimization of the energy consumption, retrofit cost and thermal comfort in a school building. The results from the optimization show the impact of each objective function on the building's overall performance after retrofit and more importantly illustrate the trade-off between different objectives. Finally, the proposed methodology highlights the improvements added to the GAINN methodology by use of a multi-objective genetic algorithm.

Uma metodologia de apoio à decisão na requalificação de edifícios para melhorar a eficiência energética e a qualidade ambiental interior

Ehsan Asadi, Ph.D.

Universidade de Coimbra, Programa MIT-Portugal, 2013

A requalificação de edifícios existentes representa uma importante oportunidade de redução do consume energético e das emissões de gases de efeito de estudo. È qualificada como uma das abordagens com mais capacidade para alcançar a sustentabilidade do ambiente construído com custos controlados e boas probabilidades de sucesso.

Embora haja disponível uma vasta gama de tecnologias de requalificação de edifícios, a escolha doss métodos para seleccionar o conjunto mais adequado de medidas de requalificação a aplicar a um edifício é ainda um grande desafio.

Os métodos devem ser categorizados em duas classes; modelos nos quais as medidas a implementar são explicitamente conhecidas a priori e modelo em que as medidas vão ser implicitamente definidas em conjunto num processo de optimização.

Esta tese foca-se na utilização de modelos e de técnicas de optimização para avaliar as escolhas de tecnologias para proporcionar um ambiente mais sustentável nos edifícios. Primeiro são desenvolvidos dois modelos, usando uma técnica clássica de optimização (Tchebycheff). A funcionalidade dos modelos propostos é avaliada através da sua aplicação ao caso de um edifício residencial. Os resultados obtidos permitem verificar a aplicabilidade da abordagem utilizada e identificar potenciais problemas que resultam da sua aplicação.Seguidamente foi desenvolvido um modelo de optimização multi-objectivo baseado em Algoritmos Genéticos integrados com Redes Neuronais Artificiais (GAINN). Os benefícios desta abordagem relativamente às técnicas clássicas de optimização, são a sua rapidez e eficiência computacional. Este modelo foi usado para a optimização do consumo energético, dos custos de requalificação e do conforto térmico de um edifício escolar. Os resultados do processo de optimização mostram o impacto de cada função objectivo no desempenho global do edifício e, mais importante, ilustram as situações de compromisso entre os diferentes objectivos. Finalmente a metodologia usada permite realçar as melhorias conseguidas, relativamente à metodologia GAINN, pela introdução de um algoritmo genético multi-objectivo.

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INTRODUCTION

Summary:

What is the current situation of energy consumption in the building sector?

What are the motivations behind this research?

What are the research goals?

Chapter 1: Introduction

1.1 CONTEXT

The energy sector faces significant challenges that everyday become more acute. The current energy trends raise great concerns about the ‘‘three Es’’ that are the environment, the energy security and the economic prosperity, as defined by the International Energy Agency (IEA-ISO 2007). The building sector is among the greatest energy consumers, using large amounts of energy and releasing considerable amounts of CO_2. In the United States in 2010, buildings accounted for 41% of the total primary energy consumption (Figure 1-1) and 74% of the electricity consumption (DOE 2012). About 40% of CO_2 emissions, 54% of SO_2, and 17% of NOx are produced in the U.S. because of building-related energy consumption.

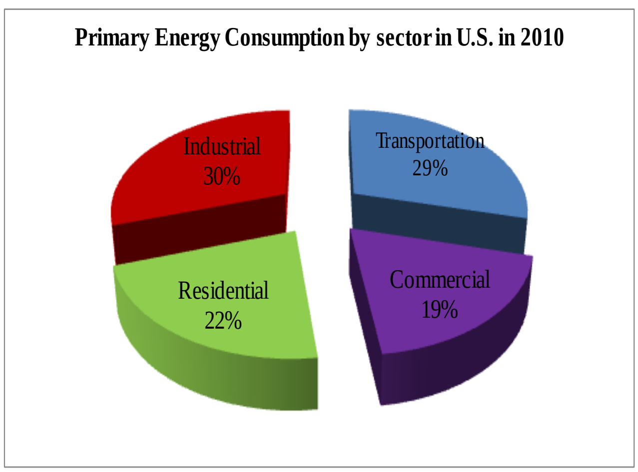

Figure 1-1 Primary energy consumption by sector in U.S. in 2010 (DOE 2012)

A similar situation is also observed in the European Union (EU), where the building sector uses 40% of the total final energy consumed (Figure 1-2) and releases about 40% of the total CO_2 emissions. In the last ten years (1999-2009), EU-27 dependency on imported energy has grown, reaching 53.9% in 2009. This represents an increase of 9 percentage points from 1999 (EUROSTAT 2011). As a consequence, the cornerstone of the European energy policy has an explicit orientation towards the conservation and rational use of energy in buildings as the Energy Performance of Buildings Directive (EPBD) 2002/91/EC (EC 2002) and its recast (EC 2010) indicate.

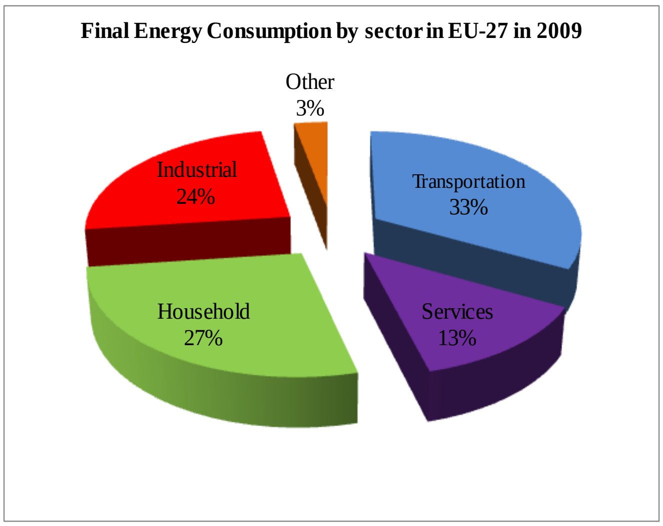

Figure 1-2 Final energy consumption by sector in EU-27 in 2009 (EUROSTAT 2011)

However, this is not a concern of only the EU, since other organizations worldwide put significant efforts towards the same direction. The International Organization for Standardization (ISO) provides another sound example through the related standards that it has published based on the work of its Technical Committee (TC) 163 for the thermal performance and energy use in the built environment (e.g. ISO 7730 2005). Moreover, the Centre Européen de Normalisation (CEN) recently introduced several new CEN standards in relation to the EPBD (e.g. prEN 15271).

Most European countries have succeeded in reducing energy consumption of new dwellings by more than 50% without increasing their building cost, and therefore energy efficiency has achieved great acceptance among building owners (Kaklauskas et al. 2006). These buildings represent about 20% of the building stock but consume only 5% of the energy. Therefore, it is essential to pay even more attention to existing buildings.

Today, it is practically feasible to reduce the energy needs in many existing buildings and, consequently, total energy demands at a national level. Therefore, concentration on improving the energetically poor building stock has great potential. Besides, the cyclical nature of the construction industry, the fact that the built environment is aging at a fast rate, the overall reduction in new building construction and the increasing awareness for sustainability, open new opportunities for expanding the retrofit and reconstruction of buildings (Shaurette 2008).

A recent report by the Construction Management Association of America (CMAA) and FMI Corporation (consulting and investment banking Co.) outlined a set of challenges that may cause construction markets to change direction in the near future. The first challenge indicated that aging infrastructure in nearly every market segment is at or beyond its current useful life. It represents trillions of dollars that are necessary to spend over the next 10 to 20 years to upgrade and replace these assets (Agostino, Mikulis & Bridgers 2007). These asset upgrades include change in use, upgrade of mechanical or electrical systems, restoration of deteriorated building envelopes, repair of structural damage, renovations to reduce serviceability problems, changes to satisfy government mandates, repair of original construction and corrections to previous renovation errors. All these actions would contribute to rationalize the energy consumption in buildings.

1.2 PROBLEM STATEMENT

Even if all future buildings were to be built so that their electrical energy and heat energy demands were very low, it would still only mean that the increase in energy demands would be reduced. It would not reduce the present demands. For many years to come, only measures taken in existing buildings will have a significant effect on the total energy demands in the building stock.

When designing new buildings, only relatively limited additional investments are often needed to make them very energy-efficient. On the other hand, it is more difficult and costly to bring about substantial energy savings in existing buildings, though it is nearly always possible to identify a number of measures that are both energy-saving and cost-effective. However, both in designing new buildings and carrying out measures in existing buildings, it is extremely important that the solution applied and the measures taken are well founded and correctly chosen (Abel & Elmorth 2007). In other words, when buildings are subject to retrofit, it is very important to select the optimal strategy at that very moment, since if other solutions are chosen and implemented it will just be possible to change the building at a later occasion at a much higher cost.

The works involved in retrofit are usually of complex and heterogeneous nature that require various specialties to be integrated in highly variable conditions. Furthermore, a thorough building's retrofit evaluation is quite difficult to undertake, because a building and its environment are complex systems regarding technical, technological, ecological, social, comfort, esthetical, and other aspects, where every sub-system influences the total efficiency performance and the interdependence between sub-systems plays a critical role (Kaklauskas, Zavadskas & Raslanas 2005).

There are a number of models and methods developed to assess conditions and support decisions pertaining to building retrofit. These methodologies can be categorized into two main approaches, the models in which alternative retrofit actions are explicitly known *a priori* and the models in which alternative retrofit actions are implicitly defined in the setting of an optimization model. The most common *a priori* approach is one in which the decision maker (DM) assigns weights to each criterion, the weighted sum of the criteria then forming a single design criterion. It is then possible to find the single design solution that optimizes the weighted sum of the criteria. However, this does not provide the designer with information about how sensitive each criterion is to changes of the other criteria.

The second approach solves this problem and enables to grasp the trade-offs between the objective functions helping to reach a satisfactory compromise solution. However, so far, relatively little attention has been paid to tackling building retrofit decision support with multiple objective analysis (Juan et al. 2009a). Therefore, this research focuses on using multiple objective optimization models and methods to assess technology choices in the built environment.

Accordingly, the problems addressed by this research can be stated as:

- A problem of society in terms of rational energy consumption;
- A problem of different organizations facing retrofit of buildings;
- A problem of designing effective decision support approaches for building retrofit;
- A problem of integrating new regulations for buildings with retrofit strategies.

1.3 RESEARCH GOALS

The general objective of this thesis is to develop a decision support approach based on multi-objective optimization techniques to assist stakeholders involved in building retrofit activities, providing the basis for a well-informed decision process taking into account all the feasible alternatives and objectives at stake without being confined to a small set of predefined scenarios. The specific goals are the following:

- Identify a set of retrofit actions and renewable energy solutions suitable for retrofitting existing buildings;
- Investigate the adequacy of the application of multi-objective optimization techniques to the problem of the improvement of energy efficiency and Indoor Environmental Quality (IEQ) in existing buildings;
- Develop an innovative multi-objective optimization methodology(s) to tackle this problem;
- Develop fully operational decision support approach(s) based on multi-objective optimization techniques;
- Quantitatively assess the application of innovative retrofit actions and renewable energy solutions for building retrofit scenarios as well as the trade-offs between the objectives;
- Explore the potential of the methodology(s) and the decision support approach(s) through the application to representative Portuguese buildings as case studies.

1.4 METHODOLOGY

This thesis focuses on using multi-objective modeling and optimization techniques to assess technology choices in the built environment. First, the research identifies a set of retrofitting actions and renewable energy solutions suitable for retrofitting existing buildings in Portugal. This sets of alternatives will then be used as an input to multi-objective optimization models to quantitatively compare the performances of different options according to multiple evaluation axes and categories of constraints, namely energy savings, retrofit cost, and thermal comfort. A representative set of Portuguese buildings including a residential and a school building are used to explore the possibilities offered by the decision support approach in a practical setting and highlight the practicability and potential problems that may arise in each proposed model.

1.5 Thesis structure

The core of the thesis is divided into 3 chapters besides Introduction and Conclusion chapters, which correspond to the 6 publications that have come out of this research: 4 published and 2 in the process of being published (Asadi et al. 2013a; 2013b; 2013; 2012a; 2012b; 2011).

Chapter 2 provides an overview of recent research and development in the field of building retrofit as well as the application of retrofit technologies to the existing buildings. The systematic approaches to building condition assessment and proper selection of effective retrofit measures are also discussed in this chapter. In particular, this chapter provides an overview on the state-of-the-art on existing building retrofit decision support approaches.

Chapter 3 is devoted to the development of two multi-objective optimization models using classical optimization methodologies, namely a Tchebycheff programming technique. The first approach uses a thermal model of the building, based on the methodology of the Portuguese building thermal code (RCCTE 2006), to assess existing building thermal performance. The second approach uses TRNSYS simulation software for energy and comfort assessment. In this chapter, both models are used to find different trade-offs between energy savings and retrofit costs in the first approach, and thermal comfort besides the already mentioned objectives in the second approach, for retrofitting a residential building in Coimbra, Portugal.

Chapter 4 presents a multi-objective optimization model based on the GAINN approach to assess technology choices in a building retrofit project. This approach combines the rapidity of evaluation of Artificial Neural Network (ANN) with the optimization power of Genetic Algorithms (GAs) in combinatorial problems. The benefits of this approach with respect to the classical optimization models are its rapidity and computational efficiency. A school building in Coimbra is used as a case study to demonstrate the practicability of the proposed approach and highlight potential problems that may arise.

Finally, Chapter 5 provides a summary of conclusions, comments on the limitations of the models, and outlines the prospects for future work.

CHAPTER 2
STATE-OF-THE-ART ON EXISTING BUILDING RETROFIT

Summary:

What are the key phases in building retrofit?

Is there any systematic approach toward building retrofit?

What are the main objectives of building retrofit?

What are the different methodologies for the assessment of building retrofit actions?

Chapter 2: State-of-the-art on existing building retrofit

2.1 INTRODUCTION

The retrofit of existing buildings offers many challenges and opportunities. The main challenge is that many uncertainties are at stake, such as climate change, services change, human behavior change, government policy change, etc., all of which directly affect the selection of retrofit technologies and hence the success of a retrofit project. The sub-systems in buildings are highly interdependent. Different retrofit measures may have different impacts on distinct building sub-systems due to these interdependencies, which make the selection of retrofit technologies very complex. Dealing with these uncertainties and system interactions is a considerable technical challenge in any building retrofit project. Other challenges may include financial limitations and barriers, perceived long payback periods, and interruptions to operations of buildings. The willingness of building owners to pay for retrofits is another challenge if there is no financial support from the government, particularly since the issue of "split incentives" is often a key factor because the retrofit cost generally falls to the building owner whereas the benefit often flows primarily to the tenants. On the other hand, building retrofit offers great opportunities for improved energy efficiency, increased staff productivity, reduced maintenance costs and better indoor comfort. It may also help to improve a nation's energy security and corporate social responsibility, reduce exposure to energy price volatility, create job opportunities and make buildings more livable (Ma et al. 2012).

According to Ma et al. (2012) the overall process of a building retrofit can be divided into five major steps (Figure 2-1). The first phase is the project setup and pre-retrofit survey. In this phase the building owners, or their agents, first need to define the scope of the work and set project targets. The available resources to frame the budget and program of work can then be determined. A pre-retrofit survey may also be required in order to better understand the building operational problems and the main concerns of occupants.

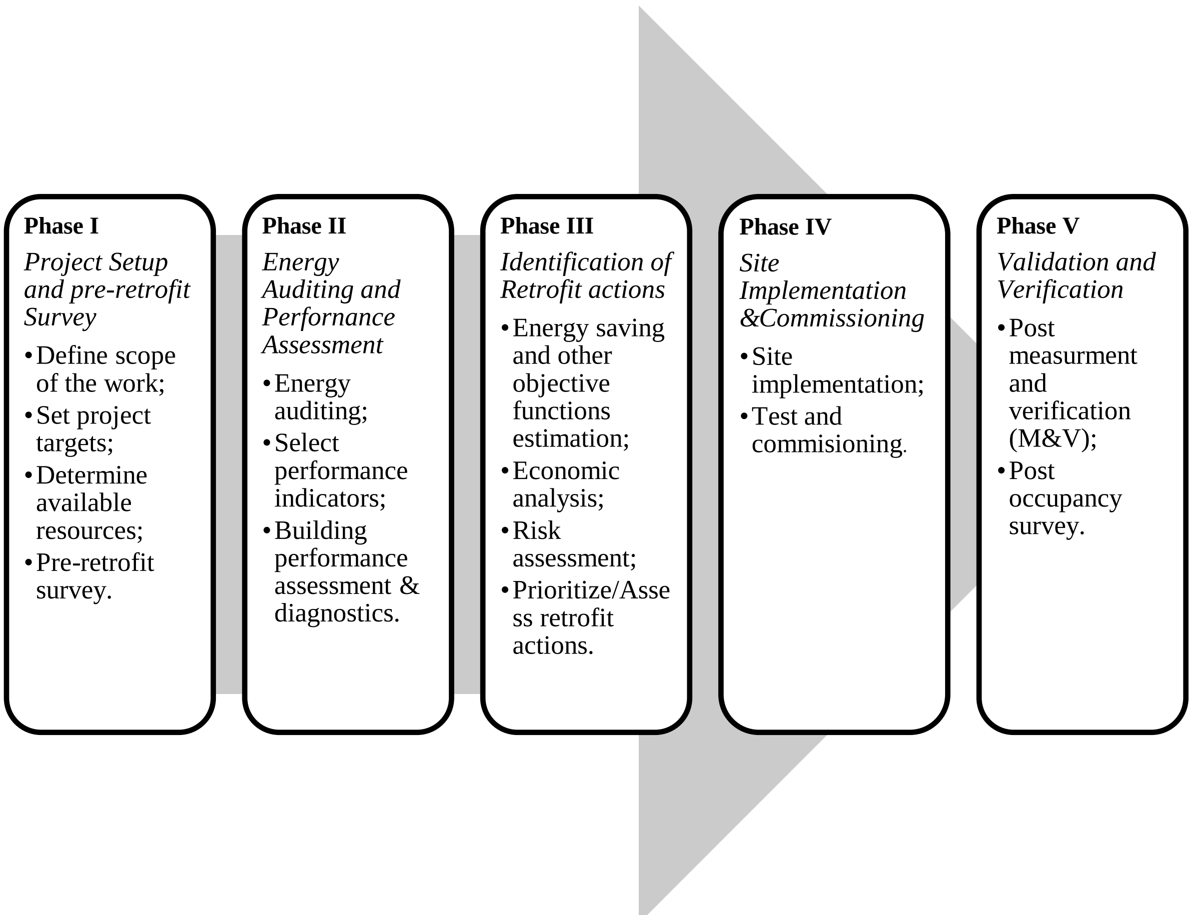

Figure 2-1 Key phases in a sustainable building retrofit program

The second phase comprises an energy audit and performance assessment (and diagnostics). Energy auditing is used to analyze building energy data, understand building energy use, identify areas with energy waste, and propose no cost and low cost energy conservation measures (ECMs). Performance assessment is employed to benchmark the building energy use by means of selected key performance indicators or green building rating systems. Diagnostics can be used to identify inefficient equipment, improper control schemes and any malfunctions in the building operation.

The third phase is the identification of Retrofit Actions (RAs). By using appropriate energy models, economic analysis tools and risk assessment methods, the performance of a range of retrofit alternatives can be assessed quantitatively. The retrofit actions can then be evaluated in terms of the selected energy-related and non-energy-related objectives such as the increase in retrofitted building market value.

The fourth phase is site implementation and commissioning. The selected retrofit measures will be implemented on-site. Test and commissioning is then employed to tune the retrofit measures to ensure the building and its service systems operate in an optimal manner. It is worth noting that the implementation of some retrofit measures may necessitate significant interruptions to the building and occupants operations.

The final phase is validation and verification of energy savings. Once the retrofit measures are implemented and well-tuned, standard measurement and verification methods can be used to verify energy savings. A post occupancy survey is also needed to understand whether the building occupants and building owners are satisfied with the overall retrofit result.

This chapter aims at providing an overview of recent research and development in the field of building retrofit as well as the application of retrofit technologies to existing buildings. The systematic approaches to building condition assessment and proper selection of effective retrofit measures are also presented herein.

2.2 Building retrofit – methodologies and strategies

A systematic approach for the improvement of building energy efficiency in its operational phase follows five general steps:

- Identification of existing building condition (Building condition assessment),
- Identification of the objective functions for building retrofit (Objectives in building retrofit),
- Identification of retrofit actions (Building retrofit technologies),
- Assessment of each option and/or strategy performance against defined objectives (Assessment methodologies),
- Measurement and verification of energy savings.

Figure 2-2 illustrates this systematic approach for identifying, determining and implementing the best retrofit measures for existing buildings based on the above mentioned steps.

2.2.1 Building condition assessment

Existing buildings tend to undergo performance degradations, change in use, and unexpected faults or malfunctions over time (Heo, Choudhary & Augenbroe 2012). These events often result in significant deterioration of the overall system performance, inefficient operation and unacceptable thermal comfort conditions. In a building retrofit project, building condition assessment is used to benchmark building energy use, identify system operational problems, assess IEQ, and identify no cost or low cost energy conservation measures.

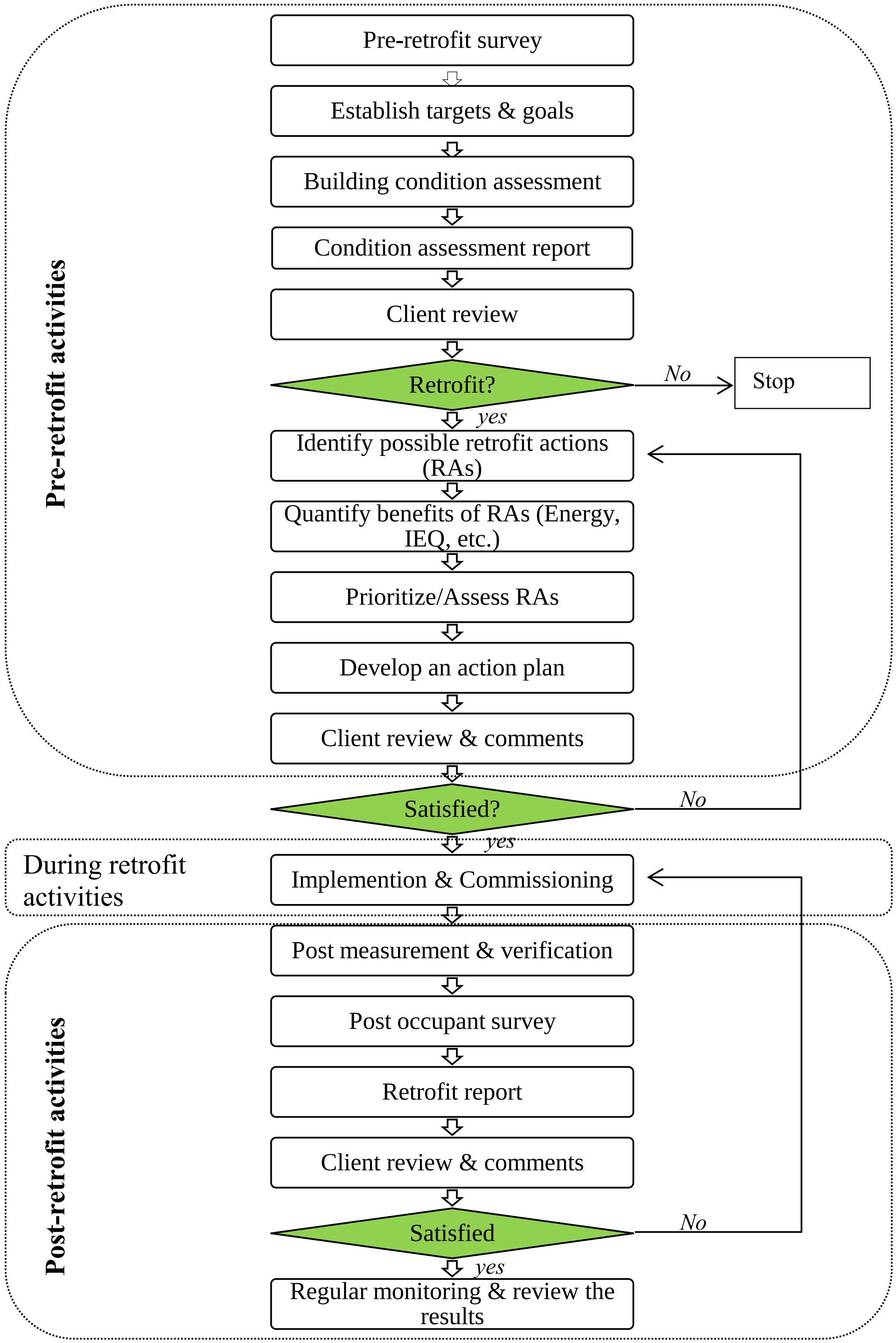

Figure 2-2 A systematic approach for the building retrofit process

In the last two decades, the development of building performance assessment tools has been very active. This is reflected in that a set of building rating tools are in the public domain, such as LEED, BREEAM, CASBEE, HKBEAM, GBTool, Green Star, NABERS, etc. These rating tools provide a framework on how to evaluate and improve building energy and environmental performance. Although these rating tools vary in scope, criteria, structure and format, the rating process is usually conducted via benchmarking the assessed building against a set of prescribed quantitative and qualitative performance indicators (PIs) of diverse objectives (Chau, Burnett & Lee 2000).

Through examination of the difference between PIs, the performance of the building can be quantified. A detailed comparison of a variety of building rating tools can be found in Haapio et al. (2008) and Reed et. al. (2009).

There is a wide range of research specifically focused on the development and application of appropriate models and strategies for building performance assessment and diagnostics. Conti et al. (1994) summarized three approaches to evaluate building energy performance, including a computational-based approach relying on input data from energy audits, a performance based approach through analysis of building utility bills, and a measurement-based approach with in situ measurement procedures. Most largely used approaches in practice are the two first ones because they are less expensive than those based on measurements. On the contrary, reliability is the main advantage of measurement-based approaches: they rely on the observation of the real behavior of the building (not on design) and allow detecting the influence of building design, operation, comfort conditions and climate on the building energy performance (Mejri, Barrio & Ghrab-Morcos 2011).

Poel et al.(2007) provided an overview of the methods and softwares that can be used to perform building energy audits and assess buildings in a uniform way, perform demands and savings calculations, provide owners with specific advice for measures to improve energy performance, and issue an energy performance certificate for existing buildings. Mejri et al. (2011) presented the application of model identification techniques for energy performance assessment of occupied buildings. Dascalaki et al. (2011) stated that building typology can be adopted as a tool for estimating the energy performance of residential buildings. It can be employed for initial energy advice activities to give building owners a quick overview of building energy performance. Song et al. (2008) developed an easy-to-use tool for fault detection and diagnosis of building air-conditioning systems. In the decision-aiding tool presented by Caccavelli and Gugerli (2002) a diagnosis package was used to evaluate the general state of office buildings with respect to deterioration, functional obsolescence, energy consumption and indoor environmental quality.

For a particular project, the appropriate performance assessment method and diagnostics tool should be selected by taking into account the client requirements, experience of energy services companies, major retrofit focus, etc.

Therefore, for the sake of this thesis, the author developed a systematic approach for indoor air quality assessment of buildings (2011; 2013). Details of the mentioned method are presented in Appendices C and D. In terms of energy assessment, specifically for the first proposed multi-objective approach which uses a thermal model to assess building and retrofit actions, the author developed a MATLAB function based on RCCTE - Portuguese Regulation for the characteristics of thermal behavior of buildings.

2.2.2 Objectives in building retrofit

The objectives for building retrofit can be either quantitative or qualitative and can be divided into four main categories depicted in Figure 2-3. (Kolokotsa et al. 2009).

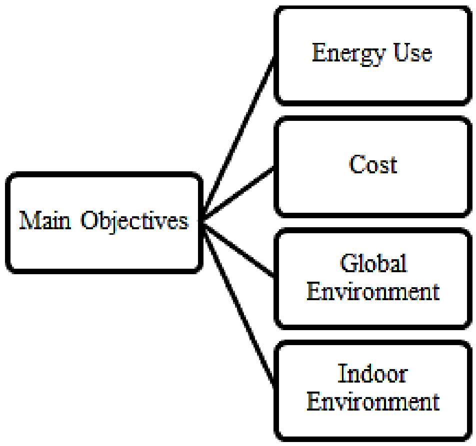

Figure 2-3 The main objectives for building retrofit (Kolokotsa et al. 2009)

More specifically, regarding energy use (primary or final), the following objectives have been utilized:

- Heating and cooling load for conditioned buildings (D'Cruz & Radford 1987; Bouchlaghem 2000);
- Normalized annual energy consumption and energy use for heating in kWh/m^2 (Rey 2004; Zhu 2006);
- Annual electricity use in kWh/m^2 (Rey 2004);
- Embodied energy (Chen et al. 2006);
- Energy and time consumption index (ETI) (Chen et al. 2006);
- Energy savings due to building retrofit in kWh/year (Gholap & Khan 2007; Asadi et al. 2012a)

Regarding costs, the following objectives have been used:

- Direct costs and initial investment costs (Rosenfeld & Shohet 1999);
- Cost of retrofit (Asadi et al. 2012a);
- Economic life span (Rosenfeld & Shohet 1999);
- Annual on-going maintenance charges(Rosenfeld & Shohet 1999; Rey 2004);
- Annual on-going charges (Rey 2004);
- Net present value (NPV) of the energy investment (Martinaitis, Kazakevicius & Vitkauskas 2007);
- Internal rate of return (IRR) of the energy investment (Martinaitis, Rogoza & Bikmaniene 2004);
- Cost of conserved energy (CCE) (Martinaitis, Rogoza & Bikmaniene 2004);
- Life cycle cost (LCC) (Wang, Zmeureanu & Rivard 2005);

As far as global environment is concerned, the objectives usually set are:

- Annual emissions GWP (global warming potential in kgeqCO_2/m^2) (Rey 2004);
- Reduction potential of global warming emissions (Alanne 2004);
- Life cycle environmental impact (Wang, Zmeureanu & Rivard 2005);
- Acidification potential in kgepSO_2/m^2 (Alanne 2004; Rey 2004)
- Water use (Alanne et al. 2007).

Indoor environmental quality and comfort have been subcategorized for the evaluation of thermal sensation, visual comfort, indoor air quality and acoustic comfort. More specifically, regarding thermal comfort, the following objectives and indicators have been used:

- PMV-PPD thermal comfort indices based on ISO-7730 standard (ISO 7730: 2005);
- Dry resultant temperature for unconditioned buildings (Bouchlaghem 2000);
- Indoor temperature and humidity (Jaggs & Palmer 2000);

- Discomfort hours during summer or winter (Roulet et al. 2002);
- Daily overheating (Rey 2004);
- Effective draught temperature index (Rutman et al. 2005);
- Summer thermal discomfort severity index, which indicates the severity of excessive mean radiant temperature during summer (Becker, Goldberger & Paciuk 2007);
- Total percentage of cumulative time with discomfort (Asadi et al. 2012b).

For visual comfort, the assessment objectives can be:

- Daylight availability (Radford & Gero 1980b);
- Lighting and visual comfort (e.g. EPIQR method, see (Bluyssen & Cox 2002; Rey 2004));
- Daylight factor (Rey 2004);
- Discomfort glare severity indicator, which indicates the annual severity of excessive discomfort glare (Becker, Goldberger & Paciuk 2007).

Indoor air quality is generally assessed via:

- CO_2 concentration index (Doukas et al. 2007);
- Maximum ratio between the mean concentration of a contaminant over the occupancy period and the contaminant's threshold limit value for short-term or long term exposure (Blondeau, Sperandio & Allard 2002);
- Ventilation rates (Blondeau, Sperandio & Allard 2002).

Acoustic comfort objectives include:

- Noise level at workplace in db (Rey 2004);
- Noise rating index (Rutman et al. 2005).

Some other descriptors not included in the previous list, but suitable for the assessment of quality of indoor environment are:

- Operative temperature (T_o) and Equivalent Temperature (T_{equi}), for thermal comfort. The percentage of permanence of indoor thermal conditions inside the comfort band defined in an adaptive comfort chart (ISO 15251: 2007), where T_o is depicted versus the outdoor mean running temperature. It is a suitable indicator of the performance of buildings without mechanical systems to provide comfortable conditions for occupants;
- Average illuminance level in the working/activity plan (ISO 8995: 2002), as regards visual comfort;
- Percentage of people dissatisfied (PD) with indoor air quality (IAQ). It can be calculated from the concentration of CO_2 using the expressions presented in (CEN 1998);
- Noise equivalent level L_{Aeq} during the working period, in db(A);
- Reverberation T of the room along the frequency spectrum of noise;
- Sound transmission index (STI).

These objectives are, in general, competing, in the sense that it is impossible to find a global solution to optimize all of them simultaneously. For this reason, several decision aid approaches have been developed for addressing the mentioned problem, namely based on multi-criteria and multi-objective models. An overview of these approaches is presented in section 2.2.4.

2.2.3 Building retrofit technologies

According to Ma et al. (2012) the retrofit technologies can be categorized into three groups: supply side management, demand side management, and change of energy consumption patterns, i.e. human factors. Figure 2-4 illustrates major possible retrofit technology types that can be used in building applications.

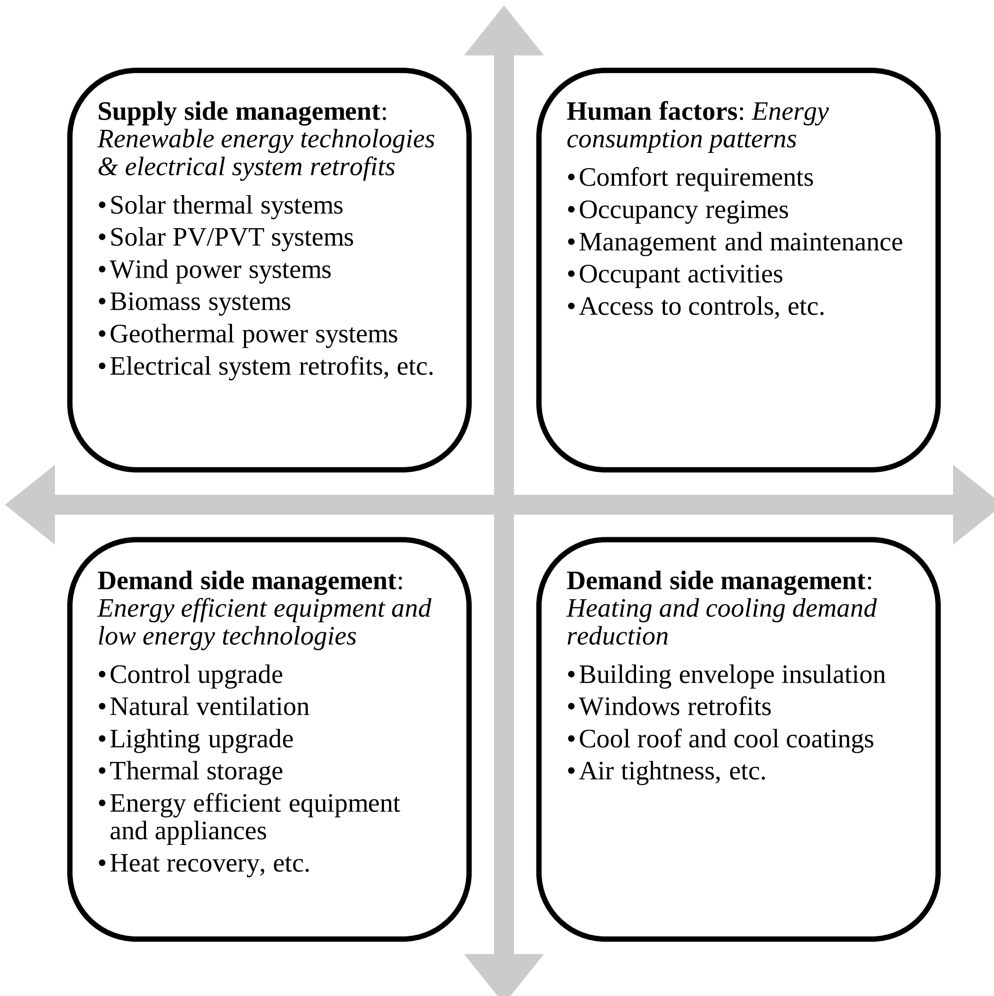

Figure 2-4 Main categories of building retrofit technologies (Ma et al. 2012)

The retrofit technologies for supply side management include electrical system retrofits and the use of renewable energy, such as solar hot water, solar photovoltaic (PV), wind energy, geothermal energy, etc., as alternative energy supply systems to provide electricity and/or thermal energy for buildings. In the last years, there has been an increasing interest in the use of renewable energy technologies as building retrofit solutions due to the increased awareness of environmental issues.

The retrofit technologies for demand side management consist of strategies to reduce building heating and cooling demand, and the use of energy efficient equipment and low energy technologies. The heating and cooling demand of a building can be reduced through retrofitting the building envelope (addition or improvement of insulation, change of color, placement of heat-insulating door and window frames, increase of thermal mass, building shaping, super insulated building envelopes, etc.) and the use of other advanced technologies such as air tightness.

Low energy technologies may include advanced control schemes, natural ventilation, heat recovery, thermal storage systems, etc.

2.2.4 Assessment methodologies

In the building retrofit, the assessment phase involves the evaluation of retrofit actions versus the selected objective functions mentioned in section 2.2.2 with respect to logical, physical and technical constraints concerning building retrofit strategies.

Therefore, the assessment procedure is an iterative procedure influenced by the objectives, the alternative actions, and set of constraints. This iterative procedure is illustrated in Figure 2-5.

The methodologies for assisting decision making in the appraisal of retrofit actions according to multiple, generally conflicting and incommensurate, evaluation aspects may be distinguished into two main approaches (Figure 2-6), according to the distinction made above of models in which alternatives are explicitly known *a priori* and alternatives are implicitly defined in the setting of an optimization model. These approaches are subcategorized and analyzed in the following sections.

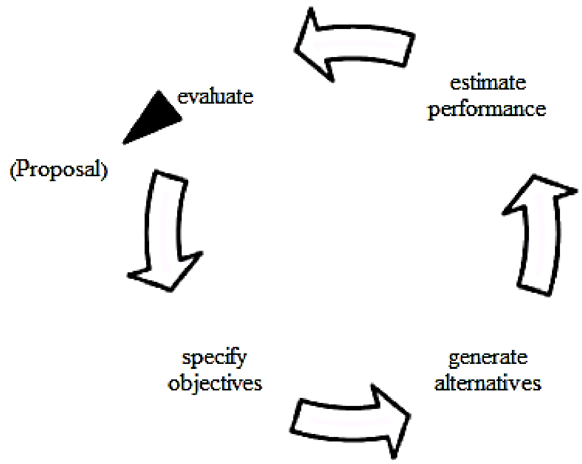

Figure 2-5 The iterative decision support process (Alanne 2004)

2.2.4.1 Alternatives explicitly known a priori

In this category there is a relatively small list of alternatives to choose from. In general an impact matrix is developed in close cooperation between the problem owners and experts, who express in a given scale the performance of each alternative for each evaluation criterion. Several methodological approaches may then be used to combine this information with the decision maker's preferences in order to reach a final recommendation that establishes a good compromise between the evaluation criteria.

Multi-criteria Decision Analysis Approaches

Traditionally, the selection of energy alternatives and retrofit actions was based only on cost optimization. The need to incorporate the environmental and social impacts of different alternatives and viewpoints of different actors in the analysis promoted the use of Multi-Criteria Decision Analysis (MCDA) methods. A wide range of MCDA methods have been applied in the energy planning area (Diakoulaki, Antunes & Martins 2005).

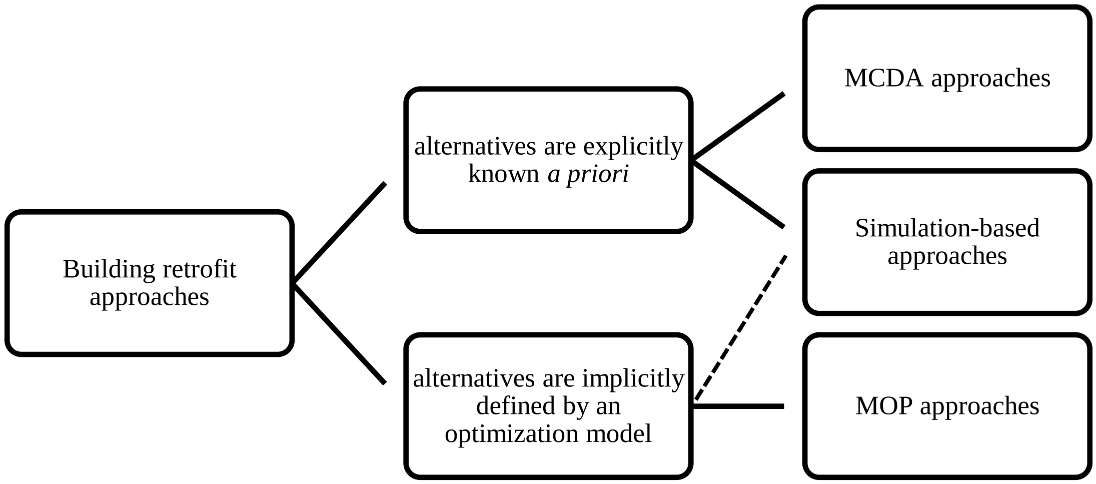

Figure 2-6 Categorization of methodological approaches for building retrofit

In an MCDA approach, it is necessary to define the problem clearly, identify the actors involved in the decision making process and their values, develop a coherent set of evaluation criteria and establish realistic alternatives. An MCDA method is selected to aggregate the performance of each alternative according to the set of criteria using the preferences elicited from the DM through technical parameters. Most MCDA methods require weighting of the criteria, although the meaning of weights may be very different from method to method. The application of MCDA methods may provide a selection of the best alternative, a ranking of the alternatives or a sorting of the alternatives in pre-defined ordered categories of merit. The most representative MCDA methods may be included into the broad classifications of methods developing an overall synthesis value (e.g., multi-attribute value/utility function approaches, AHP) and outranking based approaches (e.g., ELECTRE, PROMETHEE).

Blondeau et al. (2002) used a combination of multiple attribute utility theory (MAUT) and outranking methods to determine the most suitable ventilation strategy for a university building, i.e. to ensure the best possible indoor air quality and thermal comfort of the occupants, and the lower energy consumption in case of increased diurnal or nocturnal ventilation and/or air conditioning. It was shown that the results of the analysis were strongly dependent on the definition of the overall utility function. On the other hand, outranking methods allow to best fit the DM's way of thinking but their results are not always as clear as the ones obtained with MAUT approaches.

Roulet et al. (2002) used principal component analysis, as well as a multi-criteria ranking method based on ELECTRE III and IV algorithms, to develop a method for ranking office buildings (ORME: office rating methodology) according to an extended list of parameters, including energy use for heating, cooling and other appliances, impact on external environment, indoor environment quality, and cost.

Outranking methods are also used by Rey (2004). The ELECTRE III method is used to rank office building retrofitting strategies.

EPIQR (Energy Performance Indoor Environmental Quality Retrofit Methods for Apartment Building Refurbishment) (Jaggs & Palmer 2000) and TOBUS (Tool for Selecting Office Building Upgrading Solutions) (Caccavelli & Gugerli 2002) are other tools using MCDA techniques for aiding the selection of building retrofit actions. The TOBUS method aimed at offering a tool for selecting office building's retrofit solutions with respect to multiple criteria. One of the key elements to reach this goal was an assessment of the degree of physical degradation, extent of any degradation, extent of the necessary work to retrofit the building and costs.

Kaklauskas et al (2005) used multi-variant design and MCDA to prioritize and rank the alternative solutions for the retrofit of a building envelope. The alternatives' significance, utility degree and priority were extracted using this methodology and, as a consequence, the strongest and weakest points of the retrofit were revealed. Zavadskas et al. (2008) considered some of the problems associated with assessing the retrofit effectiveness of apartment buildings in urban areas. They offered a new approach based on multiple criteria complex proportional assessment (CORPAS) to determine the retrofit effectiveness of houses considering both expected energy savings and the increase in the market value of the renovated buildings.

Alanne (2004) combined MCDA and a multi-objective knapsack model to support building retrofit. MCDA was used to extract the utilities of the retrofit actions proposed, as well as the total utility versus the selected criteria. The utility scores obtained are then used as weights in a knapsack optimization model to identify the actions that should be undertaken, through the maximization of the objective function (that is utility score achieved by selecting the retrofit action, specified by environmental value and functionality) subject to budget constraints.

Simulation-based Approaches

Simulation-based approaches are either simplified (analytical methods) or detailed (numerical methods) using powerful simulation programs. The simplified methods are the degree-day method, the variable-base degree-day method, the bin method and the modified bin method (Al Homoud 2001).

In the simulation-based process, a basic model of the building is developed using simulation tools. Then, through an iterative procedure, a series of recommendations are defined using the best construction practice (Horsley, France & Quatermass 2003). These recommendations may include increase of insulation, change of glazing, etc.

There are a number of detailed building energy simulation packages, such as EnergyPlus, eQuest, DOE-2, ESP-r, BLAST, HVAC-SIM+, TRNSYS, etc. A detailed comparison of the capabilities of 20 building energy simulation packages can be found in (Crawley et al. 2008).

For example, TRNSYS was used by Santamouris et al. (2007) to investigate the energy saving potential of green roofs in a nursery school in Greece. EnergyPlus was used by Becker et al (2007) to assess specific factors of building design elements (window orientation, glazing type, thermal resistance of walls, etc.) and 20 ventilation strategies for schools' energy consumption and efficiency. Zmeureanu (1999) employed DOE-2 to develop an energy rating system for existing houses and estimate the energy savings potential that could be obtained by retrofitting the studied houses.

Although many sophisticated energy simulation programs are valuable to study the impacts of different ECMs on building performance, the iterative trial-and-error process of searching for a better solution is time-consuming and ineffective because of the inherent difficulty in exploring a large design space.

The main problem when employing MCDA techniques is that they are applied upon a set of predefined alternative courses of action. In case that a limited number of such alternatives have been defined, there is no guarantee that the solution finally reached is the optimal one. Also, the selection of a representative set of alternatives is usually a difficult problem, while the final solution is heavily affected by these predefined alternatives. On the opposite case, i.e. when numerous alternatives are defined, the required evaluation and selection process may become extremely difficult to handle. In any case, however, the MCDA approach limits the study to a potentially large but certainly finite number of alternatives, when the real opportunities are enormous considering all the available retrofit actions that may be employed (Diakaki, Grigoroudis & Kolokotsa 2008).

2.2.4.2 Alternatives implicitly defined in a mathematical model

Decision support for improving energy efficiency in buildings problems are also tackled using multi-objective optimization models stated as mathematical programming models with multiple competing objective functions to be optimized. In these models the set of feasible solutions is implicitly defined by a set of constraints.

Multi-objective Programming Approaches

The modeling of real-world problems generally requires the consideration of distinct axes of evaluation of the merits of potential solutions. Namely in engineering problems, aspects of operational, economic, environmental and quality of service nature are at stake. Therefore, mathematical models must explicitly address these multiple, incommensurate and often conflicting aspects of evaluation as objective functions to be optimized. In addition, multi-objective programming (MOP) models enlarge the variety of potential solutions to be considered and enable to grasp the trade-offs between the objective functions helping to reach a satisfactory compromise solution. The essential concept in multi-objective optimization is the one of non-dominated (efficient, Pareto optimal) solutions, that are feasible solutions for which no improvement in all objective functions is simultaneously possible; in order to improve an objective function it is necessary to accept worsening at least another objective function value. In real-world problems, a high number of non-dominated solutions are likely to exist. (Figure 2-7) illustrates this concept for a maximization problem for two objectives f1 (e.g. energy savings) and f2 (e.g. investment cost savings). Solution B is better than solution C as it provides higher energy savings and higher investment cost savings. Solution C performs better than solution D, as despite equal investment cost savings C achieves higher energy savings than D. However, when comparing B and E, neither can be said superior. Although solution E saves more money, it provides lower energy savings than solution B.

Solution B dominates solutions C and D, whereas a non-dominance relation cannot be established between solutions E and B. Solution A, on the other hand, is not dominated by any other solution and thus is called non-dominated or Pareto-optimal. All solutions on the dashed frontier are non-dominated.

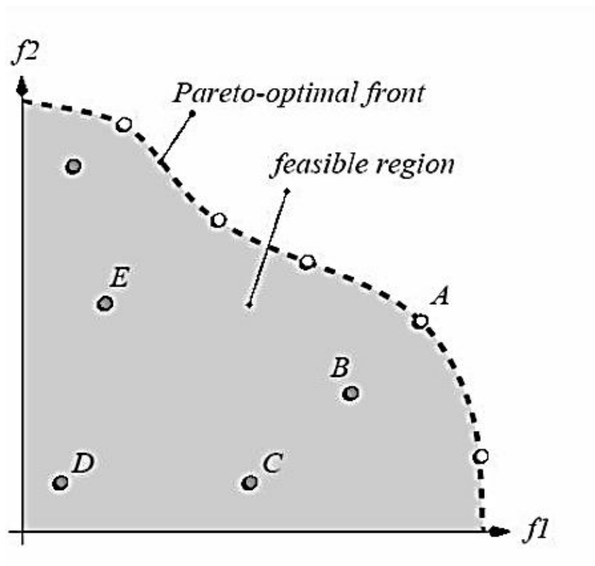

Figure 2-7 Illustrative example of Pareto optimality in the objective space

Although it is the essential concept in MOP, the concept of non-dominated solution is a “poor” one, in the sense that it lacks discriminative power for decision recommendation purposes. Non-dominated solutions are not comparable between them, so no solution naturally arises as the “final” one. The fact that multi-objective optimization enables the characterization of the non-dominated front and the trade-offs at stake between the objective functions is one of its main advantages. However, it is then necessary to reach a final compromise solution, from the set of non-dominated solutions, for practical implementation or a reduced set of non-dominated solutions for further screening. For this purpose, methods generally combine techniques to compute non-dominated solutions with mechanisms to incorporate the DM's preferences into the decision aid process.

Pareto optimization was introduced in the building area in the 1980s by Radford, Gero and D'Cruz (1980b; 1980a; 1983; 1987), and it is now widely used in building design and less in retrofit optimization.

Diakaki et al. (2008) developed a MOP model to find alternative measures for improving energy efficiency in buildings. Following this work, (Diakaki et al. 2010) extended the model to the building design phase, which allows obtaining global optimal solutions. This has been accomplished through weight coefficients that are set to define the relative importance of the objectives according to the DM's preferences.

The complexity of the decision problem resulting from the consideration of its combinatorial nature and multiple objectives has led researchers to use genetic algorithms, usually coupled with simulation tools. Wright et al. (2002) used a multi-objective genetic algorithm to find the trade-off between the energy cost and occupant thermal comfort for the design of a single zone HVAC system. Hamdy et al. (2011) proposed a MOP approach based on GA to tackle the problem of designing low-emission cost-effective dwellings, minimizing the carbon dioxide emissions and the investment cost for a two-story house and its HVAC system. Juan et al.(2009b) developed a GA based decision support system to help DMs conduct housing condition assessment and identify optimal retrofit actions considering the trade-off between cost and quality. Chantrelle et al. (2011) used a genetic algorithm coupled to TRNSYS to develop a multi-objective tool for the optimization of renovation operations, with an emphasis on building envelopes, heating and cooling loads and control strategies.

A main drawback of GA is the high burden whenever it is necessary to make a large number of calls to an evaluation function involving a high computational cost. In building applications, these evaluations are generally estimated by an external simulation program such as Computational Fluids Dynamics (CFD) or other simulation packages. If accurate results are required, each evaluation can be time consuming, and thus the complete computational process becomes extremely unattractive (Magnier 2008).

Genetic Algorithm Integrating Neural Network (GAINN) is one of the solutions to the above mentioned problem. The main idea of GAINN is to benefit from the rapidity of evaluation provided by ANN as well as the optimization power of the GA. The procedure is to first use an ANN to approximate the system being studied, and then use this ANN within the GA as the objective function. The outcome is a drastic reduction of the simulation time, while keeping an acceptable quality and reliability in the solution process.

GAINN was first used in building engineering for the optimization of chillers control (Chow et al. 2002). This study introduced the methodology to the building field, and proved its efficiency in terms of accuracy and reduction of the total optimization time. Later, GAINN has been successfully applied in other studies, such as Zhou (2007), combined with CFD, and Conraud (2008), combined with ESP-r.

Recently this approach was used by Magnier et al.(2010) using a simulation-based ANN to characterize building behavior, and then the ANN model was combined with a multi-objective GA to optimize thermal comfort and energy consumption in designing a residential building. The considered variables were divided into HVAC system-related variables and building envelope-related variables. HVAC related variables were heating and cooling temperature set points, relative humidity set points, supply air flow rate, and thermostat delays. Regarding building envelope, windows size, and building thermal mass were considered for optimization. Although this combined approach can be utilized for building retrofit actions selection, no usage of GAINN approach has been founded in the literature.

Summary of key developments from previous studies are presented in Table 2—1.

Table 2—1 Summary of key findings

	Reference	Assessment methodology	Criteria / objectives	Major retrofit actions/ improvements
MCDA Approaches	Gustafsson (2001)	mixed integer linear programming-MILP	Life cycle cost (LCC)	Fenestration retrofits
	Blondeau et al. (2002)	combinatorial & outranking methods	Comfort index, IAQ index, economic index	Ventilation strategy (ventilation only actions, air conditioning actions)
	Roulet et al. (2002) (ORME)	multi-criteria ELECTRE	energy use, discomfort hours,	N/A
	Caccavelli et al. (2002) (TOBUS)	MCDA (N/A)	Thermal comfort, IAQ, lighting, noise.	Envelope protection, passive & hybrid cooling techniques, heating system, controls in AHU, energy recovery system, low energy office equipment, water saving
	Rey et al. (2004)	ELECTRE III	Environmental, Sociocultural & economic criteria	Stabilization strategy, substitution strategy, double-skin façade strategy
	Kaklauskas et. al. (2005)	MCDA and multi-variant design	Price, mechanical strength, reliability, thermal transmission, air leakage, longevity, duration of works, waterproof-ness, pay-back period, guarantee period	Window options
	Zavadskas et al. (2008)	multiple criteria complex proportional assessment -COPRAS	Energy savings, increase in market value	Envelope, Heating system, Replacing sewage pipes, electrical equipment.
	Zhao et al. (2009)	multi index comprehensive evaluation, AHP, post-evaluation thought and successful degree evaluation method	Energy savings, heat comfort, heat cost reduction, degree of satisfaction	Heat metering and temperature regulation, building envelope, heat source and network

Simulation based Approaches	Zmeureanu et al. (1999)	Simulation based (DOE-2)	Energy savings	Envelope, air infiltration.
	Florides et al. (2002)	Simulation based (TRNSYS)	Energy consumption, life-cycle savings.	Natural & controlled ventilation, solar shading, glazing, orientation, thermal mass, building shape
	Zurigat et al. (2003)	Simulation based (TRNSYS)	Peak cooling load	Envelope insulation, space ventilation, shading, glazing, artificial lighting, evaporative cooling
MOP Approaches	Diakaki et al. (2008)	MOP (compromise programming, global criterion method, goal programming)	Building load coefficient, material cost	Window, wall insulation material and thickness
	Chantrelle et al. (2011)	MOP (GA coupled with TRNSYS)	Energy consumption, cost, thermal comfort, life-cycle environmental impact	Building envelope, control strategy

2.3 Conclusion

In this chapter an overview of recent research and development related to improvement of energy efficiency and evaluation of different retrofit technologies for building applications is provided. The major findings from previous studies are:

- A large number of innovative technologies and energy efficiency measures for building retrofit exist. The main issue is to identify those that will prove to be the more effective and reliable in the long term.
- The building retrofit assessment procedure is an iterative procedure influenced by the objectives, the alternative retrofit actions, and the sets of constraints.
- The methodologies involving multiple evaluation aspects of potential solutions for decision support in the assessment of retrofit action may be distinguished into two main approaches: approaches in which alternatives are explicitly known *a priori* and approaches in which alternatives are implicitly defined within an optimization model.
- Appropriate problem structuring methods, selection of evaluation criteria, definition of representative alternative courses of action and preference elicitation techniques are essential in MCDA approaches to select the most effective retrofit strategies.
- MCDA approaches consider that a list of predefined intervention solutions is given for which the performance in multiple (quantitative or qualitative) criteria is known at the outset. In case a small number of such solutions have been defined, there is no guarantee that the solution finally reached is the best one (from the DM's perspective). On the other hand, when a large number of solutions are

defined the required evaluation and selection process may become extremely difficult to handle.

- Recently more attention has been paid to the use of MOP techniques for the problem of improving energy efficiency in buildings. These approaches based on comprehensive mathematical models aim at providing a thorough characterization of the trade-offs between different objectives.
- The use of GA to deal with MOP models for building retrofit decision support has gained an increasing relevance due to its ability to deal with complex mathematical models and avoid being trapped in local non-dominated solutions.
- A major drawback of the application of GA in building efficiency improvement is the high number of calls to the evaluation function associated with physical parameters, which is generally estimated by an external simulation program such as CFD or other simulation software. If accurate results are required, each evaluation can be time consuming and thus the complete computational process becomes extremely unattractive.
- GAINN is one of the techniques to deal with this problem by approximating the system under study by an ANN whose results are then used within the GA.

Based on this extensive literature review, the thesis therefore focuses on using multi-objective optimization models to quantitatively assess technology choices in a building retrofit project. The proposed models take into account all feasible combinations of choices without being confined to a small set of predefined scenarios in building retrofit.

The thesis uses classical optimization methodologies, namely Tchebycheff programming coupled with a thermal model at the first step and then a simulation program to assess passive retrofit actions for a residential building in use. Then the thesis focuses on the use of a multi-objective optimization model based on GAINN approach. This model not only improves the optimization efficiency but also makes the methodology closer to real-world scenarios.

CHAPTER 3
MULTI-OBJECTIVE OPTIMIZATION OF A RESIDENTIAL BUILDING USING A TCHEBYCHEFF OPTIMIZATION TECHNIQUE

Summary:

What are the different components of a multi objective optimization model for buildings retrofit?

What are the retrofit actions considered in this study?

What are the approaches considered for building and retrofit actions assessment?

What is the optimization approach used to tackle the problem in this study?

What are the results from the application of the methods to a real world case study?

Chapter 3: Multi-objective Optimization of a residential building using a Tchebycheff optimization technique

This chapter presents two multi-objective optimization models to assess technology choices in a building retrofit project: thermal-model based and simulation-based approaches. Both models are tackled using a Tchebycheff optimization technique. These models are able to take into account all feasible combinations of choices, without being confined to a small set of predefined scenarios in building retrofit. To this end, an actual residential building is used to illustrate the feasibility of the proposed approaches and highlight potential problems that may arise in each one. A wide decision space is considered, including alternative materials for the external walls insulation, roof insulation, different window types, and installation of a solar collector in the existing building. The DM is offered solutions corresponding to different trade-offs between energy savings and retrofit costs in the first model, and thermal comfort besides the already mentioned objectives in the second model. A solution to obtain a desired efficiency label at minimum cost can also be identified.

3.1 Thermal model-based multi-objective optimization

In this section a multi-objective model is presented to obtain satisfactory compromise retrofit actions according to the DM's preferences. This model is applied to a real-world case study and the results are discussed.

3.1.1 Multi-objective optimization problem

The development of a multi-objective optimization model for buildings retrofit strategies requires the definition of appropriate decision variables, objective functions and constraints, and finally the selection of appropriate solution techniques. The decision variables reflect the total set of alternative measures that are available for retrofitting of a building (e.g. windows, insulation material, etc., see §2.2.3). The objectives to be achieved (e.g. minimum retrofit cost, maximum energy savings, etc., see §2.2.2) are defined using the appropriate linear or non-linear mathematical formulation. Moreover, the set of feasible solutions is delimitated with respect to logical, physical and technical constraints concerning the decision variables. Constraints can also be added to enforce acceptability thresholds for the objective functions of the problem.

3.1.2 Decision variables

The set of retrofit actions in this step concerns combinations of choices regarding external wall insulation materials, roof insulation materials, windows, and installation of solar collector to the existing building. Therefore, four types of decision variables are defined concerning the alternative choices regarding:

- the external wall insulation materials;
- the roof insulation materials;
- the windows type;
- the solar collector type.

For simplicity, it is assumed that only one retrofit action from each four set of actions may be selected for the building retrofit.

Assuming availability of *I* alternative types of external wall insulation material, *J* alternative types of roof insulation material, *K* alternative types of window, and *L* alternative types of solar collector, binary variables x_i^{EWAL} with i = *1,...,I*; x_j^{ROF} with j = *1,...,J*; $x_k^{WIN}$with k = *1,...,*K; and $x_l^{SC}$with l = *1,...,*L are defined as follows:

$$x_i^{EWAL} = \begin{cases} 1, & if\ insulation\ material\ type\ i\ is\ selected \\ 0, & otherwise \end{cases} \tag{3.1}$$

$$x_j^{ROF} = \begin{cases} 1, & if\ insulation\ material\ type\ j\ is\ selected \\ 0, & otherwise \end{cases} \quad (3.2)$$

$$x_k^{WIN} = \begin{cases} 1, & if\ window\ type\ k\ is\ selected \\ 0, & otherwise \end{cases} \quad (3.3)$$

$$x_l^{SC} = \begin{cases} 1, & if\ solar\ collector\ type\ l\ is\ selected \\ 0, & otherwise \end{cases} \quad (3.4)$$

3.1.3 Objective functions

3.1.3.1 Energy savings

The general procedure for estimating the energy savings, ES, from a retrofit project is based on the calculation of the difference between the pre-retrofit energy consumption predicted from a model and the post-retrofit energy consumption (Krarti 2000):

$$ES = E_{pre} - E_{post} \quad (3.5)$$

where

- E_{pre} - the energy use predicted from a pre-retrofit model of the facility [kWh/year];
- E_{post} - the energy used in the facility after implementing the retrofit actions [kWh/year].

Therefore, it is important to develop a model for the building before estimating the retrofit energy savings. To limit the computational time, a simple thermal model of the building is developed based on current methodology of the Portuguese building thermal code (RCCTE), which is based on ISO-13790 (2007).

In general, the energy sources in a building are used for space heating, cooling and domestic hot water (DHW) systems and for electric lighting (in this specific model electric lighting is not considered). The building energy needs (E) are calculated using equation (3.6):

$$E = Q_{ic} + Q_{vc} + Q_{ac} \tag{3.6}$$

where

- Q_{ic} - Annual energy need for space heating [kWh/year];
- Q_{vc} – Annual energy need for space cooling [kWh/year];
- Q_{ac} – Annual energy need for domestic hot water [kWh/year].

A steady-state yearly-based calculation methodology is used here to estimate the heating and cooling needs of residential buildings, as well as the domestic hot water needs. The heating needs are obtained applying a degree-days method and the envelope heat balance for the heating season. The cooling needs are obtained from the average difference between the indoor-outdoor temperature and the envelope heat balance during the cooling period. The DHW needs are obtained applying the average daily reference consumption and the annual number of days of DHW consumption.

Energy need for heating

The annual building energy need for space heating, $Q_{ic}(x)$ (x denotes the vector of the decision variables defined in §3.1.2), for conditions of continuous heating, is calculated according to equations (3.7 – 3.14):

$$Q_{ic}(x) = Q_t(x) + Q_v - Q_{gu}(x) \tag{3.7}$$

$$Q_t(x) = Q_{ext}(x) + Q_{enu} + Q_{pt} \tag{3.8}$$

$$Q_{ext}(x) = 0.024. DD_H. BLC_{ext}(x) \tag{3.9}$$

$$BLC_{ext}(x) = \frac{A_{EWAL}}{\sum_{i=1}^{I} x_i^{EWAL} d_i/\lambda_i} + \frac{A_{ROF}}{\sum_{j=1}^{J} x_j^{ROF} d_j/\lambda_j} + A_{win} \sum_{k=1}^{K} U_k . x_k^{WIN} \tag{3.10}$$

$$Q_{enu} = 0.024. DD_H. U_{enu}. A_{enu} \tag{3.11}$$

$$Q_{pt} = 0.024. DD_H. \sum_m \Psi_m . B_m \tag{3.12}$$

$$Q_v = 0.024. \left(0.34. ACH. A_p. P_d\right). DD_H \tag{3.13}$$

$$Q_{gu}(x) = \eta_{aq} \left[\left(0.720. A_p. M. q_i\right) + \left(M. G_{south}. \sum_o X_o. A_{e,k}. x_k^{WIN} \right) \right] \tag{3.14}$$

where

Coefficients:

- τ – Losses to non-heated spaces reduction coefficient [kWh/year];
- Ψ – Linear heat flux transmission coefficient [W/(m.ºC)];
- X_o –Orientation coefficient for the different façade orientations;

Parameters:

- $Q_t(x)$ – Total heat loss by the building envelope [kWh/year];
- Q_v – Total heat loss by air renovation [kWh/year];
- $Q_{gu}(x)$ – Total heat gains (internal + solar heat gains through glazing) [kWh/year];
- $Q_{ext}(x)$ – Total heat loss through zones in contact with outdoor (walls, glazing, roofs and pavements) [kWh/year];

- Q_{enu} – Total heat loss through zones in contact with non-heated spaces (walls, glazing, roofs and pavements) [kWh/year];
- Q_{pt} – Total heat loss through linear thermal bridges [kWh/year];
- DD_H – Heating degree-days [ºC.day];
- $BLC_{ext}(x)$ – Building load coefficient [W/ ºC];
- A_{EWAL} – Exterior wall surface area [m^2];
- d_i – Thickness of the external wall insulation type i [m];
- λ_i - Thermal conductivity of the external wall insulation material type i [W/(m.ºC)];
- A_{ROF} - Roof surface area [m^2];
- d_j - Thickness of the roof insulation type j [m];
- λ_j - Thermal conductivity of the roof insulation material type j [W/(m.ºC)];
- A_{WIN} – Windows surface area [m^2];
- U_k – Window type k thermal transmission coefficient [W/(m^2.ºC)];
- $A_{enu} -$ Area of building envelope elements in contact with non-heated spaces [m^2];
- $U_{enu} -$ Thermal transmission coefficient of elements in contact with non-heated spaces [W/(m^2.ºC)];
- B – Floor or wall interior linear perimeter for envelope in contact with the soil or interior length of thermal bridge [m];
- ACH – Air changes per hour [h^{-1}];
- Ap – Net floor area [m^2];
- P_d – Floor to ceiling height [m];
- η_{aq} – Heat gains utilization factor for heating season;
- M – Heating season duration [Months];

- q_i – Internal heat gains [W/m^2];
- G_{south} – Average monthly solar energy that reaches a south oriented vertical surface [kWh/(m^2.month)];
- A_e – Effective glazing area for the different windows orientations [m^2].

Energy need for cooling

The annual cooling needs are obtained applying the following equation:

$$Q_{vc}(x) = \left(1 - \eta_{arref}\right).(Q_1(x) + Q_2 + Q_3 + Q_4(x)) \tag{3.15}$$

$$Q_1(x) = 2.928.BLC_{ext}(x).(\theta_m - 25) + BLC_{ext}(x).[(\alpha.Ir)/h_e] \tag{3.16}$$

$$Q_2 = 2.928.(0.34.ACH.A_p.P_d)(\theta_m - 25) \tag{3.17}$$

$$Q_3 = 2.928.A_p.q_i \tag{3.18}$$

$$Q_4(x) = \sum_{o} Ir.A_{WIN}F_S F_g F_W g_{\perp ver} x_k^{WIN} \tag{3.19}$$

where:

Coefficient

- F_S – Shading factor;
- F_g – Glazing factor;
- F_W – Correction factor for movable shading devices for cooling calculation;
- $g_{\perp ver}$ – Effective total solar energy transmittance of glazing;
- Ir – Total average solar radiation intensity for each orientation [kWh/m^2];
- α – Exterior envelope solar radiation absorption coefficient;

Parameters:

- θ_m– Average outdoor temperature in the cooling season [˚C];

- η_{arref} − Heat gain utilization factor for cooling season;
- h_e − Thermal conductivity of external building envelope, that is equal to 25 [W/m^2.ºC];
- Q_1 – Total heat gains through building envelope [kWh/year];
- Q_2[1] – Total heat transfer due to air infiltration [kWh/year];
- Q_3 – Total internal heat gains [kWh/year];
- Q_4 – Total heat gains through glazing [kWh/year].

Energy needs for water heating

The DHW needs are obtained applying the following equations:

$$Q_{ac}(x) = (\frac{Q_a}{\eta_a} - E_{solar}(x) - E_{ren}) \tag{3.20}$$

$$Q_a = \frac{M_{AQS} \times 4187 \times nd \times \Delta T}{3600000} \tag{3.21}$$

$$E_{solar}(x) = \sum_{l}^{L} E_l^{sol}.x_l^{sc} \tag{3.22}$$

where:

Coefficient:

- η_a – DHW system efficiency;

Parameters:

- M_{AQS} – Average daily consumption of DHW [L/day];
- nd– Total number of days with DHW consumption;
- ΔT − Difference of temperature to heat the water [˚C];
- $E_l^{sol}(x)$– Total energy contribution from solar collector type l [kWh/year];

[1] This term is a negative heat gain, as the average outdoor temperature is always less than indoor air set-point temperature in cooling season (Annex III, RCCTE).

- E_{ren} – Total energy contribution from other renewable sources [kWh/year];
- Q_{ac} – Annual DHW heating needs [kWh/year];
- Q_{a}- Total energy supplied with conventional systems for DHW [kWh/year].

3.1.3.2 Retrofit cost

The investment cost for the retrofit of building is simply calculated by adding the cost terms corresponding to retrofit actions as follows:

$$ReCost(x) = A_{EWAL} \sum_{i=1}^{I} C_i^{EWAL} . x_i^{EWAL} + A_{ROF} \sum_{j=1}^{J} C_j^{ROF} . x_j^{ROF} + A_{WIN} \sum_{k=1}^{K} C_k^{WIN} . x_k^{WIN} + \sum_{l=1}^{L} C_l^{SC} . x_l^{SC} \quad (3.23)$$

where:

- C_i^{EWAL} – cost in [€/m^2] for external wall insulation material type *i*;
- C_j^{ROF} - cost in [€/m^2] for roof insulation material type *j*;
- C_k^{WIN}- cost in [€/m^2] for window type *k*;
- C_l^{SC}- cost for solar collector type *l*.

3.1.4 Model and solution techniques

Using the decision variables, objective functions and constraints developed above, the multi-objective programming model is formulated:

$$\begin{gathered}
Min \;\; Z_1(x) = ReCost(x) \\
Max \;\; Z_2(x) = ES(x) \\
S.t. \\
\sum_{i=1}^{I} x_i^{EWAL} = 1 \\
\sum_{j=1}^{J} x_j^{ROF} = 1 \\
\sum_{k=1}^{K} x_K^{WIN} = 1 \\
\sum_{l=1}^{L} x_l^{SC} = 1 \\
x_i^{EWAL} \in \{0,1\} \;\; \forall \; i \in \{1,2,\dots,I\} \\
x_j^{ROF} \in \{0,1\} \;\; \forall \; j \in \{1,2,\dots,J\} \\
x_k^{WIN} \in \{0,1\} \;\; \forall \; k \in \{1,2,\dots,K\} \\
x_l^{SC} \in \{0,1\} \;\; \forall \; l \in \{1,2,\dots,L\}
\end{gathered} \tag{3.24}$$

A Tchebycheff programming technique has been developed in MATLAB (Mathworks 2010) to tackle this multi-objective optimization model. To apply Tchebycheff programming, the decision model is rearranged to aggregate the two objective functions. In this method weighting vectors *p* are used to define different weighted Tchebycheff metrics (Steur 1986). As a first step, the ideal solution Z^* should be computed (in the following equation, *S* denotes the feasible solutions set):

$$\begin{aligned}
Z_i^* &= max\,\{Z_i(x) | x \in S\} \qquad if\ Z_i\ to\ be\ maximized \\
Z_i^* &= min\,\{Z_i(x) | x \in S\} \qquad if\ Z_i\ to\ be\ minimized
\end{aligned} \tag{3.25}$$

The problem is then formulated in a way to compute the solutions closest to Z^*, according to the Tchebycheff metric:

$$\begin{gathered}
Min\ \{\alpha\} \\
s.t. \\
\alpha \geq (Z_1(x) - Z_1^*)\left(\frac{p_1}{Z_1^*}\right) \\
\alpha \geq \left(Z_2^* - Z_2(x)\right)\left(\frac{p_2}{Z_2^*}\right) \\
\alpha \geq 0 \\
\sum_{i=1}^{I} x_i^{EWAL} = 1 \\
\sum_{j=1}^{J} x_j^{ROF} = 1 \\
\sum_{k=1}^{K} x_K^{WIN} = 1 \\
\sum_{l=1}^{L} x_l^{SC} = 1 \\
x_i^{EWAL} \in \{0,1\} \ \ \forall \ i \in \{1,2,\dots,I\} \\
x_j^{ROF} \in \{0,1\} \ \ \forall \ j \in \{1,2,\dots,J\} \\
x_k^{WIN} \in \{0,1\} \ \ \forall \ k \in \{1,2,\dots,K\} \\
x_l^{SC} \in \{0,1\} \ \ \forall \ l \in \{1,2,\dots,L\}
\end{gathered} \tag{3.26}$$

In this formulation, p_1 and p_2 are two constants representing the weight of each objective. These weights can be changed to obtain different compromise solutions. For strictly positive weight values this formulation yields solutions that are non-dominated (efficient, Pareto optimal): for each of these solutions there is no other solution able to improve one of the objectives without worsening the other objective.

3.1.5 Model application on a residential building

This section is aimed at illustrating how this approach can be used to provide decision support for selecting a satisfactory compromise solution based on the MOP model. The building under study is a semi-detached house (one family) building, situated in central region of Portugal (Figure 3-1 and Figure 3-2), for which the number of degree days, the heating season duration, the average temperatures and the corresponding solar radiations were extracted from the national regulation RCCTE. The building has one ground floor and a basement. Its total pavement area and average height are equal to 96.6 m^2 and 2.47 m, respectively.

Figure 3-1 The case study: view of the single-family house

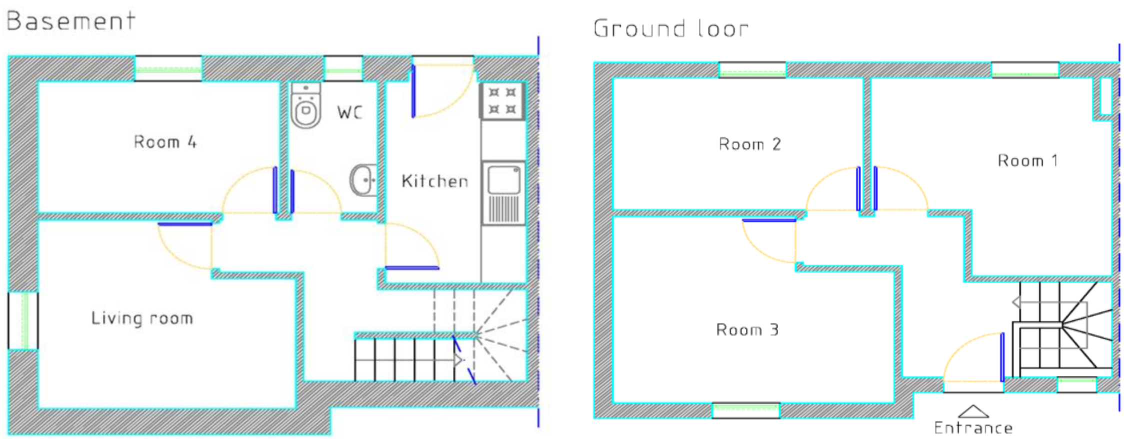

Figure 3-2 Schematic plan of basement and ground floor of case study

The building has a concrete structure. The walls are in concrete with no thermal insulation; the window frames are wooden with single glass. Its main façade is oriented toward south-east. The construction characteristics of the building under study are presented in Table 3—1 to Table 3—3.

Table 3—1 Glazing characteristics

Orientation	Area [m^2]	U [W/m^2.K]	g(%)
Northwest	0.89	3.40	0.88
Northwest	0.89	3.40	0.88
Southeast	0.89	3.40	0.88
Southeast	1.60	4.60	0.88
Southeast	0.59	6	0.88
Southwest	0.89	3.40	0.88
Northwest	0.89	3.40	0.88
Southwest	1.27	3.90	0.88
Southwest	1.27	3.90	0.88

Table 3—2 External wall characteristics

Orientation	Area [m^2]	U [$W/m^2.K$]	Exterior color
Southeast	15.38	2.13	Light color
Southwest	11.11	2.13	Light color
Northwest	5.76	2.13	Light color
Northeast	23.70	1.70	Light color
Southwest	16.22	1.70	Light color
Northwest	10.50	1.70	Light color
Southeast	12.10	2.37	Light color
Southwest	13.72	2.37	Light color
Northwest	14.14	2.37	Light color
Northeast	1.32	2.37	Light color

Table 3—3 Internal wall characteristics

Description	Area [m^2]	U [$W/m^2.K$]
Internal wall	4.05	1.79
Internal wall	2.18	2.15
Internal wall	4.35	1.47
Neighboring house	11.52	2.00
Neighboring house	10.25	2.00
Internal pavement	58.73	1.71

According to the Portuguese regulations, internal temperatures for heating and cooling periods have been set to $\theta_{iH} = 20°C$ and $\theta_{iC} = 25°C$, respectively. Temperature rise for heating water has been set to 45ºC. In addition, the internal heat gain per unit of floor area is set to 4 (W/m^2).

For heating, cooling and hot water supply, electricity is taken into account as the source, while solar energy is only considered for hot water supply.

After introducing the required data into an excel spreadsheet, the developed program imports the data into MATLAB automatically for further analysis, including prediction of the building energy use before retrofit.

The summary of results from energy analysis of the building before retrofit is reported in Table 3—4.

Table 3—4 Building energy analysis before retrofit

Building performance indicators		
Estimated global annual primary energy need for heating, cooling and water heating	12.89	[kgoe/(m^{2}year)]
Existing building total energy need	31641.58	[kWh/year]
Existing building Energetic Classification	C	
Existing building CO_2 emission	1.4945	[TCO_2/year]

The decisions regarding the building retrofit are related to the alternative choices regarding:

- the external wall insulation materials (56 different types);
- the roof insulation materials (16 different types);
- the windows type (21 different types);
- the solar collector type (10 different types).

Different retrofit actions and their related characteristics are extracted from CYPE rehabilitation price generator (CYPEingenieros 2010) and presented in Appendix B.1.

After the energy analysis of the building, the non-dominated solutions to the MOP problem that optimize each objective function individually are computed (solutions S1 and S2 in Table 3—5) using the function *bintprog* in MATLAB's optimization toolbox. The components of the ideal solution, which is the initial reference point, are displayed in bold italic. Besides, the row numbers of corresponding retrofit actions leading to the S1 and S2 solution, as well as the building energy classification after implementing the related retrofit action package, are reported in Table 3—5.

Table 3—5 Non-dominated solutions that optimize individually each objective function (Refer to Appendix B.1 for RAs characteristics)

Solution	ReCost (€)	ES (kWh/year)	EWAL insulation	ROF insulation	WIN type	Solar collector	Energy classification
S1	***1791***	15263	46	1	1	6	C
S2	5901	***25539***	56	17	15	8	B

The non-dominated solution that minimizes the Tchebycheff distance (that is, minimizes the largest deviation) to the ideal solution is then computed for different combinations of objective function weight coefficients, which makes the construction of an efficient frontier possible. Table 3—6 shows the objective functions values for the scenarios at an equally spaced number of p values. As the weight coefficient of the energy saving objective increases, the solution to problem (3.26) approaches and finally reaches (when $p_1 = 0$, $p_2 = 1$) its optimal solution. On the other hand, as the weight coefficient of the retrofit cost objective function increases, the solution approaches its optimal solution.

Table 3—6 Solutions obtained applying Tchebycheff programming with different weights (Refer to Appendix B.1 for RAs characteristics)

p_1	p_2	ReCost (€)	ES (kWh/yr)	EWAL insulation	ROF insulation	Window Type	Solar Collector	Energy Classification
1.00	0.00	1791	15263	46	1	1	6	C
0.95	0.05	1814	19316	48	6	1	6	B-
0.90	0.10	1834	20229	35	6	1	6	B-
0.85	0.15	1848	20766	36	6	1	6	B-
0.80	0.20	1865	21165	37	6	1	6	B-
0.75	0.25	1884	21473	26	6	1	6	B-
0.70	0.30	1902	21765	26	8	1	6	B-
0.65	0.35	1922	22010	27	8	1	6	B-
0.60	0.40	1941	22306	26	7	2	6	B-
0.55	0.45	1961	22551	27	7	2	6	B-
0.50	0.50	1983	22769	27	9	2	6	B-
0.45	0.55	2005	22876	27	10	8	6	B-
0.40	0.60	2057	23025	33	10	8	6	B-
0.35	0.65	2108	23126	53	10	2	6	B-
0.30	0.70	2117	23158	53	10	8	6	B-
0.25	0.75	2245	23339	53	9	15	6	B-
0.20	0.80	2361	23511	54	8	2	6	B-
0.15	0.85	2395	23712	54	10	8	6	B-
0.10	0.90	2729	24047	54	17	15	6	B-
0.05	0.95	3043	24564	54	10	8	7	B
0.00	1.00	5901	25539	56	17	15	8	B

The values from Table 3—6 were used to construct the plot shown in Figure 3-3, displaying some of the points that lie on the non-dominated solution frontier. Choosing each solution from this frontier will lead to different energy classification of the building according to RCCTE. In terms of retrofit actions, we can note that in the left hand side of the curve a small increase of retrofit cost can lead to improvement of energy classification of the building from C to B- On the right hand side, the situation is more difficult, and to improve energy classification of the building from B- to B, a large amount of investment is required. This case highlights the major advantage of a multi-objective formulation, which is to provide a thorough understanding of the trade-offs between the competing objectives, and bring the potential of each investment into focus. In the current case the building owner could be easily convinced to slightly increase the amount of investment from €1791 to €1814 in order to improve energy classification of the building by one level.

Figure 3—4 demonstrates how the objective values change in relation with the specific value of the weights. This figure clearly shows the competitive nature of the objective functions. As the weight on energy saving (p_2) increases, the set of actions leading to higher energy savings and at the same time higher cost have been selected.

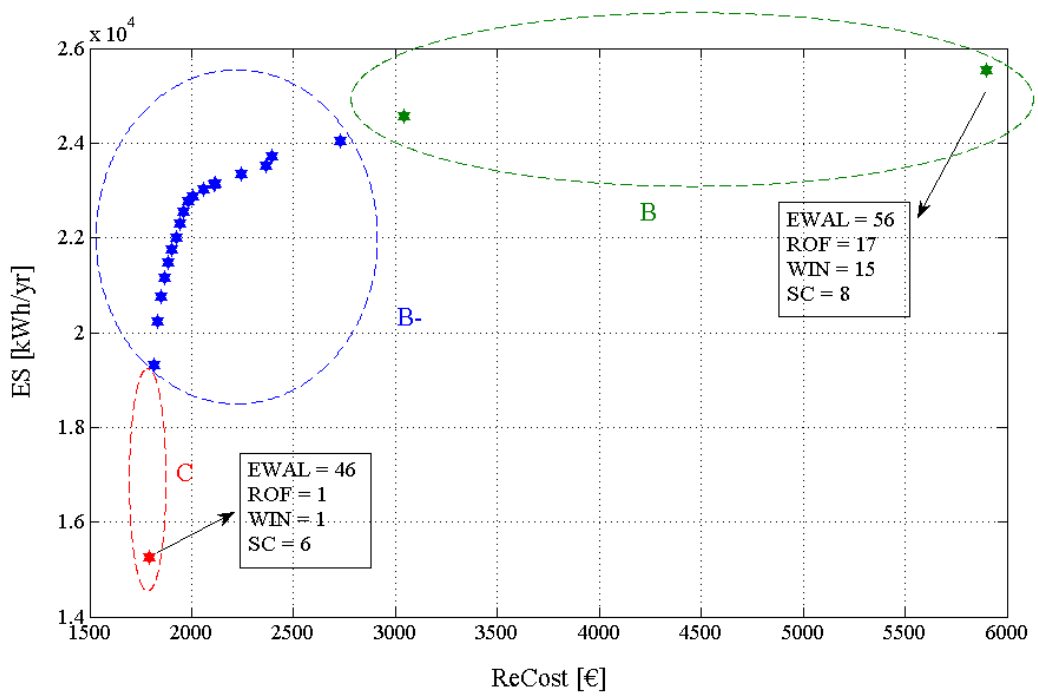

Figure 3-3 Results of multi-objective optimization of retrofit cost and energy savings (Refer to Appendix B.1 for RAs characteristics)

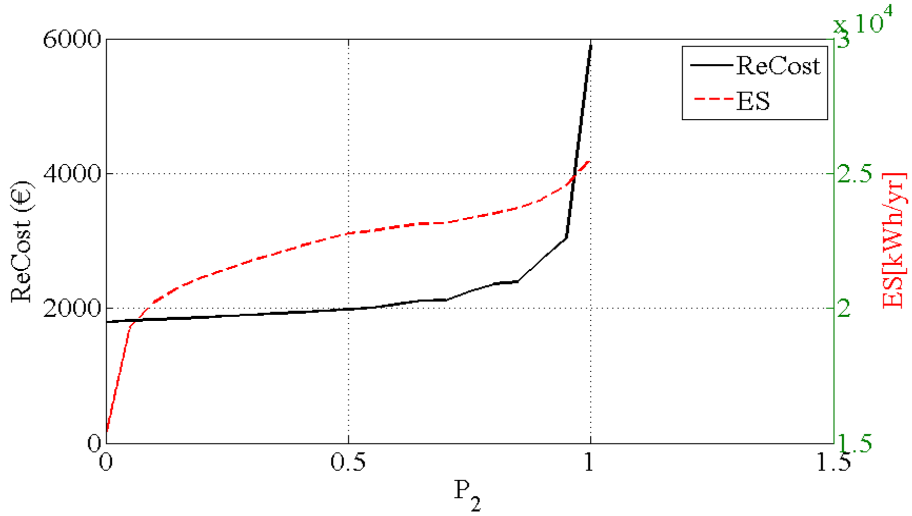

Figure 3-4 Objective functions variation with the corresponding weights.

3.1.6 Discussion

This section presented a thermal-based multi-objective mathematical model to provide decision support in the evaluation of technology choices for the building retrofit strategies. The model allows explicitly for simultaneous consideration of all available combinations of alternative retrofit actions. It also allows for the consideration of logical, physical and technical constraints. The result of the application of Tchebycheff programming technique, employed for the solution of model under study, shows the feasibility of this methodology to find well balanced strategies for retrofitting of buildings to be presented to a DM in the context of a decision support process.

However, since retrofit action assessment is based on the developed thermal model of the building which is based on the current methodology of RCCTE, the model is not able to perform a detailed analysis of building. Therefore, it does not allow for consideration of all desired objective functions such as thermal comfort. Moreover, this thermal code is developed for residential buildings, so application of the model for other types of building is not adequate.

3.2 SIMULATION-BASED MULTI-OBJECTIVE OPTIMIZATION

Following the previous thermal-based multi-objective optimization model, this section aims to extend that initial modelling approach. The extended approach incorporates also thermal comfort as an additional objective function. Moreover, the model is not constrained to buildings of a particular type, since the simulation program is used for building and its retrofit actions assessment.

This section is organized as follows. The problem formulation and the optimization approach are presented in section 3.2.1. The application of the model to the previous case study is described in section 3.2.2, which is followed by a discussion of the results.

3.2.1 Optimization approach

The scheme of the proposed simulation-based optimization approach is illustrated in Figure 3-5. The scheme is a combination of TRNSYS 16, GenOpt 3.0.3 and optimizer under MATLAB environment. TRNSYS (2009) is a transient system simulation program with a modular program structure that was designed to solve complex energy systems problems. GenOpt is an optimization program for the minimisation of a cost function that is evaluated by an external simulation program (Wetter 2009). In this work the capability of GenOpt for parametric runs is used only to perform automatic simulation of the building.

In this scheme a model of the building before retrofit is firstly created in TRNSYS. Then, using this model and GenOpt results are obtained for the implementation of each retrofit action.

Finally, an optimizer developed in MATLAB was run to evaluate potential solutions. A Tchebycheff programming procedure developed in the previous section is used to tackle the multi-objective optimization problem.

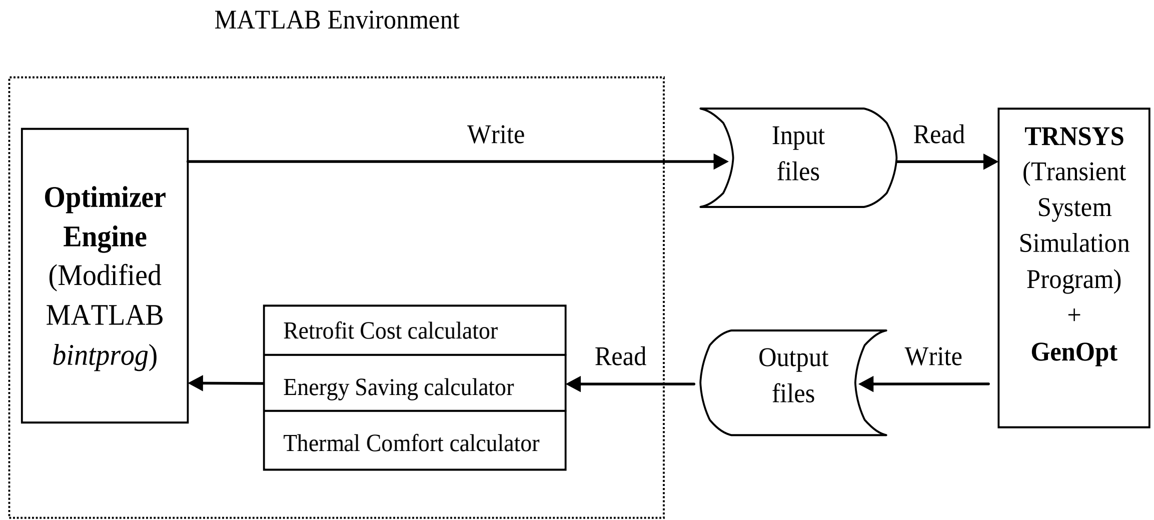

Figure 3-5 Optimization framework

3.2.2 Formulation of the optimization problem

Definition of the multi-objective optimization (MOO) problem for buildings retrofit strategies requires the definition of appropriate decision variables, objective functions and constraints, and finally the selection of appropriate solution computation techniques.

3.2.2.1 Decision variables

The set of retrofit actions in this section is the same as the previous case study, namely decision variables concerning combinations of choices regarding external walls insulation material, roof insulation material, window types and installation of solar collector in the existing building. For further information regarding the decision variables refer to section 3.1.2.

3.2.2.2 Objective functions

The objectives of this optimization model are to minimize Retrofit Cost and Total Percentage of discomfort hours, and maximize Energy Savings due to the implementation of retrofit actions.

Retrofit Cost (ReCost)

As it is mentioned in section 3.1.3.2, the overall investment cost for the building retrofit, ReCost(x) (x denotes the vector of all decision variables defined in Section 3.1.2) is calculated by adding individual retrofit action costs (Expression 3.23)

Energy Savings (ES)

As in section 3-1-3-1, the general procedure for estimating the energy savings, ES, from a retrofit project is based on the calculation of the difference between the pre-retrofit energy demand predicted using a model and the post-retrofit energy demand. However, in this section E_{pre} (the building energy demand before retrofit) and E_{post} (the building energy demand after implementing the retrofit actions) are derived from building simulation with TRNSYS.

$$E = E_{heat} + E_{cool} + E_{DHW} \tag{3.27}$$

in which E_{heat} is the annual energy demand for space heating [kWh/year], E_{cool} is the annual energy demand for space cooling [kWh/year], and E_{DHW} is the annual energy demand for domestic hot water system [kWh/year].

The computation of E_{Post} is made using the individual effects computed for space heating, space cooling and domestic hot water (3.28-3.30).

$$E_{heat}(x) = \sum_{i=1}^{I} E_{heat,i}^{EWAL}.x_i^{EWAL} + \sum_{j=1}^{J} E_{heat,j}^{ROF}.x_j^{ROF} + \sum_{k=1}^{K} E_{heat,k}^{WIN}.x_k^{WIN} \quad (3.28)$$

where $E_{heat,i}^{EWAL}$ represents total energy demand [kWh/year] for space heating after implementation of external wall insulation material type i, $E_{heat,j}^{ROF}$ represents total energy demand [kWh/year] for space heating after implementation of roof insulation material type j and $E_{heat,k}^{WIN}$ represents total energy demand [kWh/year] for space heating after implementation of window type k. All the mentioned energy demands are predicted by the simulation model.

$$E_{cool}(x) = \sum_{i=1}^{I} E_{cool,i}^{EWAL}.x_i^{EWAL} + \sum_{j=1}^{J} E_{cool,j}^{ROF}.x_j^{ROF} + \sum_{k=1}^{K} E_{cool,k}^{WIN}.x_k^{WIN} \quad (3.29)$$

where $E_{cool,i}^{EWAL}$ is total energy demand [kWh/year] for space cooling after implementation of external wall insulation material type i, $E_{cool,j}^{ROF}$ is total energy demand [kWh/year] for space cooling after implementation of roof insulation material type j and $E_{cool,k}^{WIN}$ [kWh/year] is total energy demand for space cooling after implementation of window type k. All the mentioned energy demands are predicted by the simulation model.

$$E_{DHW}(x) = \sum_{l=1}^{L} E_{DHW,l}^{SC}.x_l^{SC} \quad (3.30)$$

where $E_{DHW,l}^{SC}$ represents total energy demand [kWh/year] for domestic hot water system after implementation of solar collector type l and is predicted by the simulation model.

Thermal Comfort (TPMVD)

The metric used to assess thermal comfort is the predicted mean vote (PMV), based on Fanger's model (Fanger 1970). PMV is representative of what a large population would think of a thermal environment, and is used to assess thermal comfort in standards such as ISO7730 (2005) and ASHRAE 55 (2004). It ranges from -3 (too cold) to +3 (too warm), and a PMV value of zero is expected to provide the lowest percentage of dissatisfied people (PPD) among a population (Figure 3-6). In this study, an absolute value of 0.7 for PMV, the upper limit of the less exigent comfort category in ISO 7730, is considered as the borderline of the comfort zone. So, in order to maximize thermal comfort, the total percentage of cumulative time with discomfort (|PMV| >0.7) over the whole year, that from now on will be mentioned as "total percentage of discomfort hours (TPMVD(X))", should be minimized. The TPMVD(X) is also predicted by TRNSYS.

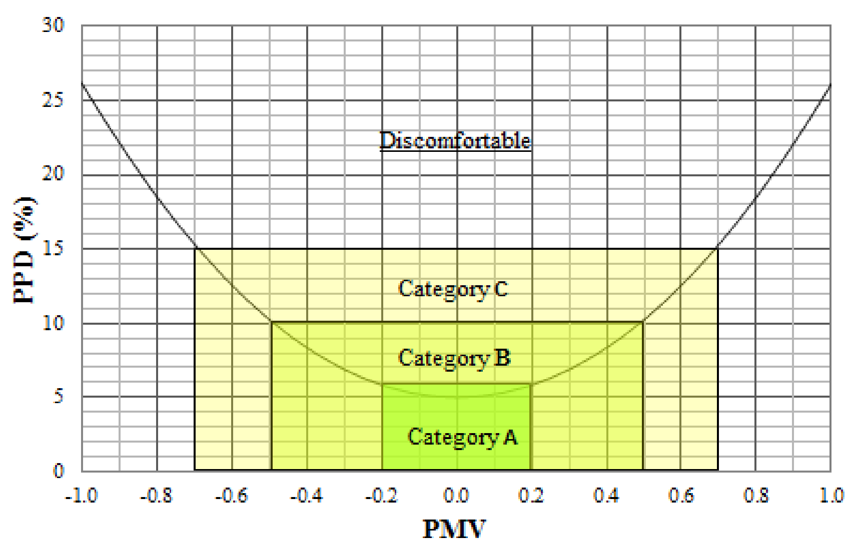

Figure 3-6 Thermal comfort of the human body as a whole (ISO 7730 2005)

3.2.3 Multi-objective optimization approach

The decision variables, objective functions and constraints developed above, lead to the formulation of the multi-objective programming problem (3.31):

$$
\begin{gathered}
Min\ Z_1(x) = ReCost(x) \\
Max\ Z_2(x) = ES(x) \\
Min\ Z_3(x) = TPMVD(x) \\
\text{S.T.} \\
\sum_{i=1}^{I} x_i^{EWAL} = 1 \\
\sum_{j=1}^{J} x_j^{ROF} = 1 \\
\sum_{k=1}^{K} x_k^{win} = 1 \\
\sum_{l=1}^{L} x_l^{SC} = 1 \\
x_i^{EWAL} \in \{0,1\}\ \forall\ i \in \{1,2,\dots,I\} \\
x_j^{ROF} \in \{0,1\}\ \forall\ j \in \{1,2,\dots,J\} \\
x_k^{WIN} \in \{0,1\}\ \forall\ k \in \{1,2,\dots,K\} \\
x_l^{SC} \in \{0,1\}\ \forall\ l \in \{1,2,\dots,L\}
\end{gathered}
\tag{3.31}
$$

Problem (3.31) is a combinatorial multi-objective problem, in which the objective functions including retrofit cost, energy savings and total percentage of discomfort hours are conflicting.

The model has been implemented in MATLAB and a Tchebycheff programming procedure has been developed to tackle the multi-objective optimization.

To apply Tchebycheff programming, the decision model is rearranged to aggregate the three objective functions. In this method weighting vectors "*p*" are used to define different weighted Tchebycheff metrics. As a first step, the ideal solution Z^* should be computed, as follows:

$$Z_i^* = max\{Z_i(X) |\, X \in S\} \qquad if\ Z_i\ to\ be\ maximized \tag{3.32}$$

$$Z_i^* = min\{Z_i(X) |\, X \in S\} \qquad if\ Z_i\ to\ be\ minimized \tag{3.33}$$

The problem is then formulated in a way to compute the solutions closest to Z^* according to weighted metrics. The (weighted) Tchebycheff metric minimizes the largest (weighted) deviation to the ideal solution. Therefore, the problem for three objective functions is formulated as follows:

$$\begin{gathered}
Min\ (\alpha) \\
\text{S.T.} \\
\alpha \geq (Z_1(x) - Z_1^*)\left(\frac{p_1}{Z_1^*}\right) \\
\alpha \geq (Z_2^* - Z_2(x))\left(\frac{p_2}{Z_2^*}\right) \\
\alpha \geq (Z_3(x) - Z_3^*)\left(\frac{p_3}{Z_3^*}\right) \\
\alpha \geq 0 \\
\sum_{i=1}^{I} x_i^{EWAL} = 1 \\
\sum_{j=1}^{J} x_j^{ROF} = 1 \\
\sum_{k=1}^{K} x_k^{WIN} = 1 \\
\sum_{l=1}^{L} x_l^{SC} = 1
\end{gathered} \tag{3.34}$$

$$x_i^{EWAL} \in \{0,1\} \;\forall\; i \in \{1,2,\dots,I\}$$
$$x_j^{ROF} \in \{0,1\} \;\forall\; j \in \{1,2,\dots,J\}$$
$$x_k^{WIN} \in \{0,1\} \;\forall\; k \in \{1,2,\dots,K\}$$
$$x_l^{SC} \in \{0,1\} \;\forall\; l \in \{1,2,\dots,L\}$$

In this formulation, $((p_1, p_2, p_3) \in \bar{\Lambda}$ are constants representing the weight of each objective, where:

$$\bar{\Lambda} = \left\{(p_1, p_2, p_3) \in R^3 \mid p_i \geq 0, \sum_{i=1}^{3} p_i = 1\right\} \quad (3.35)$$

For strictly positive weight values this formulation yields solutions that are non-dominated (efficient, Pareto optimal): for each of these solutions there is no other feasible solution able to improve one of the objectives without worsening, at least, one of the other objectives. These weights can be changed to obtain different compromise solutions. In this work weights have been used to sample the entire decision space and provide the DM a sub-set of non-dominated solutions that is representative of different trade-offs at stake in different regions of the decision space, thus avoiding an exhaustive computation. For this purpose, weights have been changed with a given step, while respecting $p_1, p_2, p_3 \in \bar{\Lambda}$. The aim is to offer the DM usable information for actual decision purposes; for instance, grasping that in a certain region of the decision space it is necessary to sacrifice cost a significant amount to gain just a small amount in the energy savings objective function.

3.2.4 Model application on a residential building

The same building as described in section 3.1.5 was selected to apply the developed model. To reduce the execution time of simulation, a simplified model is used to represent the house as a single zone. A one year simulation was run in TRNSYS to determine the heating, cooling, domestic hot water demands as well as PMV values. Type

109 and Type 56 were used for the weather condition and building definition in TRNSYS. Some of the parameters (besides the building characteristics) introduced in Type 56 of TRNSYS were: 2 occupants with the activity level of 1 met (1 met = 58.15 W/m^2) in the room; total internal heat gain due to equipment and lighting equal to 4 W/m^2; infiltration rate of 0.9 air changes/hour.

In this work, PMV values are also calculated by TRNSYS, using a constant metabolic rate 1 met, a constant air velocity of 0.1 m/s, and a clothing factor equal to 0.5 clo in summer, 0.9 clo in winter, and 0.8 during the rest of the year. A summary of the results from the energy analysis of the building before retrofit is reported in Table 3—7.

Table 3—7 Building performance before retrofit

Building performance indicators	
Total annual heating demand	216.35 [kWh/(m^{2}year)]
Total annual cooling demand	4.95 [kWh/(m^{2}year)]
Total annual DHW demand	52.33 [kWh/(m^{2}year)]
Total annual energy consumption	273.63 [kWh/(m^{2}year)]

A list of alternative retrofit actions is presented in Appendix B.2. Typical retrofit actions including different external wall insulation materials, roof insulation materials, window types and solar collectors have been introduced in the list aiming at improving the building energy savings and thermal comfort in a cost effective manner.

After energy analysis of the building, the non-dominated solutions to the MOO problem that individually optimize each objective function are computed (solutions S1, S2 and S3 in Table 3—8) using the modified function *bintprog* in MATLAB's optimization toolbox. The components of the ideal solution (the individual optima to each objective function), which is the initial reference point, are displayed in bold italics. That is, the reference point in the objective function space consists in the individual optima to the multiple objective functions, which cannot be attained simultaneously since the functions are conflicting. Table 3—8 also indicates the solution configuration that is the identification of the corresponding retrofit actions leading to each solution.

When retrofit cost is optimized independently of the other objective functions, the external wall and roof insulation material, window and solar collector with minimum cost are selected; however, this results in minimum energy savings.

Table 3—8 Non-dominated solutions that optimize each objective (Refer to Appendix B.2 for RAs characteristics)

Solution	Type of solution	ReCost(€)	ES(kWh/year)	TPMVD	EWAL	ROF	WIN	SC
S1	[min] ReCost	***2843.15***	9065.06	83.79	1	7	1	1
S2	[max] ES	7245.52	***12792.15***	93.07	24	18	3	4
S3	[min] TPMVD	4374.83	12284.48	***82.69***	16	1	2	1

On the other hand, when the energy savings objective is individually optimized, the external wall and roof insulation material and window with the minimum thermal transmittance are selected. Furthermore, a solar collector with the highest area and energy efficiency is selected. However, the retrofit actions combination results in a significant increase of the retrofit cost. Surprisingly, the total percentage of discomfort hours (total percentage of time with |PMV| >0.7) has also increased, even comparing with the building before retrofit, which can be justified through the selection of the roof insulation and a window with minimum thermal transmittance (maximum thermal resistance), so higher indoor temperatures lead to a high percentage of discomfort hours.

Finally, when the “total percentage of discomfort hours” over the whole year is optimized, another solution configuration is obtained, which leads to an energy savings objective function not far from its optimal value but at a significantly lower cost.

As stated earlier, a Tchebycheff programming approach has been used to compute compromise non-dominated solutions displaying different trade-offs between the objective functions, thus sampling the non-dominated frontier. The non-dominated solution that minimizes the Tchebycheff distance to the ideal solution (taken as the unreachable reference point) is then computed for different combinations of objective function weight coefficients using a modified version of the *bintprog* function in MATLAB, which makes the construction of the non-dominated frontier possible. As the first step, the first two objective functions (retrofit cost and energy savings) are considered simultaneously, and then the third objective (total percentage of discomfort hours) is added. This stepwise procedure intends to make a better constructive use of the 2D and 3D graphical representation of non-dominated frontier in order to unveil and further discuss the corresponding solutions and trade-offs at stake between the competing objectives.

Figure 3-7 shows the non-dominated solutions for the first two objectives. Figure 3-8 demonstrates how the objective values change in relation with the specific value of the weights (each point depicts the compromise obtained for a different combination of weight values). This figure clearly shows the competitive nature of objective functions energy savings and retrofit costs. As the weight on energy savings (p_2) increases, the set of actions leading to higher energy savings and at the same time higher cost are selected.

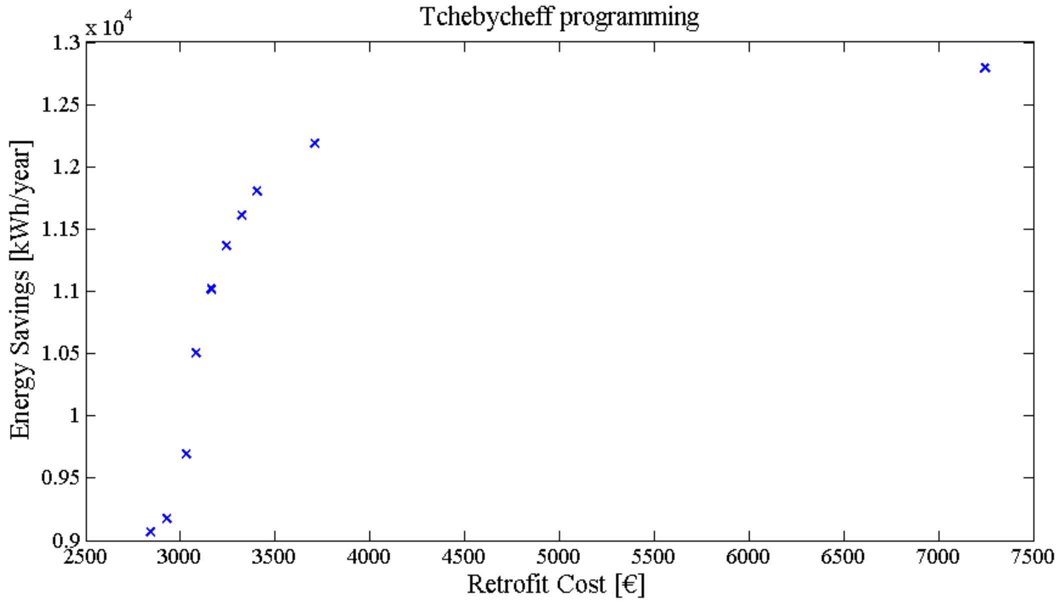

Figure 3-7 Multi-objective solutions for the building retrofit strategies (two objective functions)

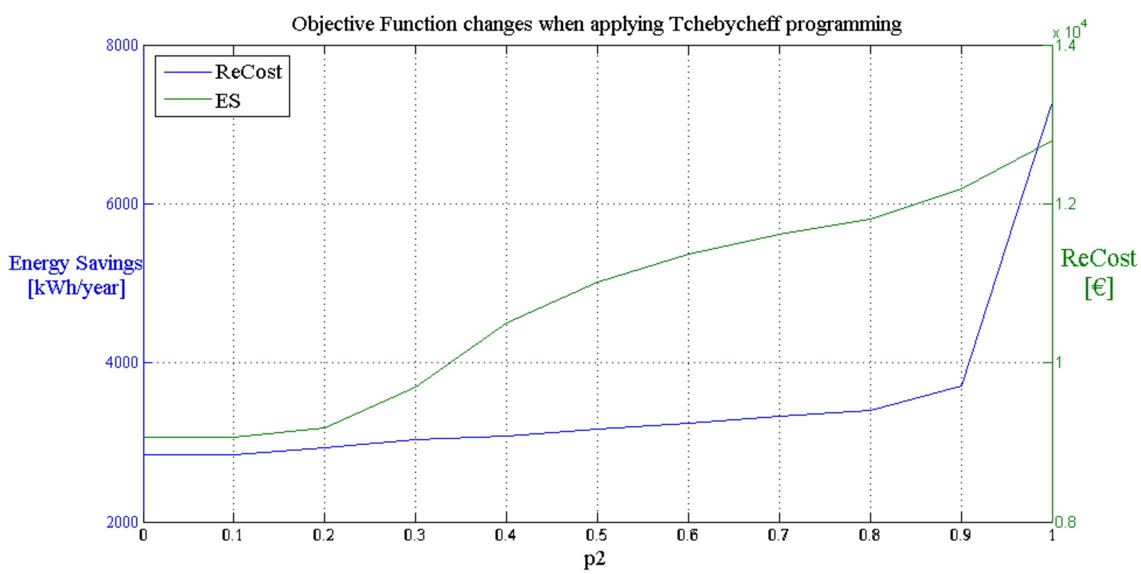

Figure 3-8 Objective functions changes with respect to weights in the Tchebycheff formulation.

After adding the third objective function (TPMVD), the compromises corresponding to different weight coefficient values are illustrated in Figure 3-9 and Table 3—9. For intermediary values of the weight coefficients, several solutions are obtained that favour each objective function at a higher or lower level depending on the specific values that have been selected. From Figure 3-9 it is seen that solutions leading to more energy savings or higher retrofit cost do not necessarily lead to a lower percentage of discomfort hours, and accordingly better thermal comfort. This case highlights the advantage of a true multi-objective optimization model, which is able to provide the DM a thorough understanding of the decision situation, namely concerning the trade-offs at stake and shedding light on the potential of each investment option.

3.2.5 Discussion

This section described an optimization methodology based on a combination of TRNSYS, GenOpt and a multi-objective optimization approach developed in MATLAB. The proposed approach was applied to a real world case study, and the results demonstrate its practicability to provide decision support in an actual setting. This allows explicitly for the simultaneous consideration of all available combinations of alternative retrofit actions. Besides, as TRNSYS is used for building condition assessment and retrofit actions evaluation, the consideration of different objective functions became possible.

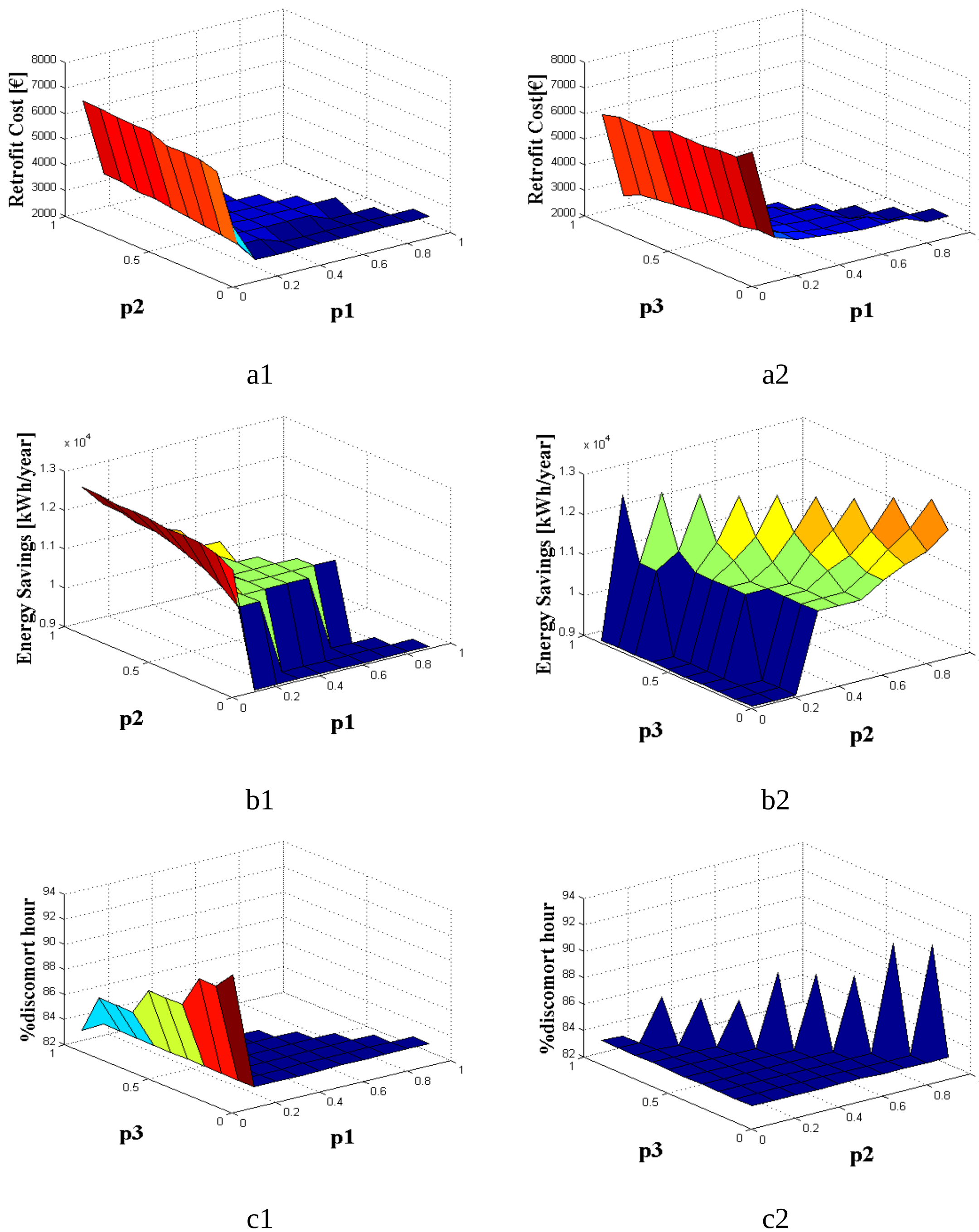

Figure 3-9 Compromise solutions for different weights: retrofit cost vs energy saving (a1) and discomfort hours(a2), Energy saving vs retrofit cost (b1), and discomfort hours (b2), discomfort hours vs retrofit cost (c1), and energy saving (c2).

Table 3—9 Sample of non-dominated solutions obtained using Tchebycheff programming (Refer to Appendix B.2 for RAs characteristics)

p1	p2	p3	ReCost(€)	ES(kWh/year)	TPMVD(%)	EWAL	ROF	WIN	SC
1	0	0	2843	9065	83.79	1	7	1	1
0.9	0.1	0	2843	9065	83.79	1	7	1	1
0.9	0	0.1	2843	9065	83.79	1	7	1	1
0.8	0.2	0	2843	9065	83.79	1	7	1	1
0.8	0.1	0.1	2843	9065	83.79	1	7	1	1
0.8	0	0.2	2843	9065	83.79	1	7	1	1
0.7	0.3	0	3163	11017	83.77	10	7	1	1
0.7	0.2	0.1	2843	9065	83.79	1	7	1	1
0.7	0.1	0.2	2843	9065	83.79	1	7	1	1
0.7	0	0.3	2843	9065	83.79	1	7	1	1
0.6	0.4	0	3163	11017	83.77	10	7	1	1
0.6	0.3	0.1	3163	11017	83.77	10	7	1	1
0.6	0.2	0.2	2843	9065	83.79	1	7	1	1
0.6	0.1	0.3	2843	9065	83.79	1	7	1	1
0.6	0	0.4	2843	9065	83.79	1	7	1	1
0.5	0.5	0	3163	11017	83.77	10	7	1	1
0.5	0.4	0.1	3163	11017	83.77	10	7	1	1
0.5	0.3	0.2	3163	11017	83.77	10	7	1	1
0.5	0.2	0.3	3163	11017	83.77	10	7	1	1
0.5	0.1	0.4	2843	9065	83.79	1	7	1	1
0.5	0	0.5	2843	9065	83.79	1	7	1	1
0.4	0.6	0	3243	11363	83.72	11	7	1	1
0.4	0.5	0.1	3163	11017	83.77	10	7	1	1
0.4	0.4	0.2	3163	11017	83.77	10	7	1	1
0.4	0.3	0.3	3163	11017	83.77	10	7	1	1
0.4	0.2	0.4	3163	11017	83.77	10	7	1	1
0.4	0.1	0.5	2843	9065	83.79	1	7	1	1
0.4	0	0.6	2843	9065	83.79	1	7	1	1
0.3	0.7	0	3324	11611	83.71	12	7	1	1
0.3	0.6	0.1	3243	11363	83.72	11	7	1	1
0.3	0.5	0.2	3243	11363	83.72	11	7	1	1
0.3	0.4	0.3	3163	11017	83.77	10	7	1	1
0.3	0.3	0.4	3163	11017	83.77	10	7	1	1
0.3	0.2	0.5	3163	11017	83.77	10	7	1	1
0.3	0.1	0.6	2843	9065	83.79	1	7	1	1
0.3	0	0.7	2843	9065	83.79	1	7	1	1
0.2	0.8	0	3404	11801	83.69	13	7	1	1
0.2	0.7	0.1	3404	11801	83.69	13	7	1	1
0.2	0.6	0.2	3324	11611	83.71	12	7	1	1
0.2	0.5	0.3	3324	11611	83.71	12	7	1	1
0.2	0.4	0.4	3243	11363	83.72	11	7	1	1
0.2	0.3	0.5	3243	11363	83.72	11	7	1	1
0.2	0.2	0.6	3163	11017	83.77	10	7	1	1
0.2	0.1	0.7	3163	11017	83.77	10	7	1	1
0.2	0	0.8	2843	9065	83.79	1	7	1	1
0.1	0.9	0	3707	12185	83.68	15	7	2	1
0.1	0.8	0.1	3707	12185	83.68	15	7	2	1

0.1	0.7	0.2	3570	12065	83.71	14	7	2	1
0.1	0.6	0.3	3570	12065	83.71	14	7	2	1
0.1	0.5	0.4	3486	11949	83.69	14	7	1	1
0.1	0.4	0.5	3404	11801	83.69	13	7	1	1
0.1	0.3	0.6	3324	11611	83.71	12	7	1	1
0.1	0.2	0.7	3243	11363	83.72	11	7	1	1
0.1	0.1	0.8	3163	11017	83.77	10	7	1	1
0.1	0	0.9	2843	9065	83.79	1	7	1	1
0	1	0	7246	12792	93.07	24	18	3	4
0	0.9	0.1	6754	12770	91.64	24	16	2	4
0	0.8	0.2	6754	12770	91.64	24	16	2	4
0	0.7	0.3	6690	12709	89.06	24	3	2	4
0	0.6	0.4	6690	12709	89.06	24	3	2	4
0	0.5	0.5	6690	12709	89.06	24	3	2	4
0	0.4	0.6	6421	12647	86.82	24	2	2	4
0	0.3	0.7	6421	12647	86.82	24	2	2	4
0	0.2	0.8	6421	12647	86.82	24	2	2	4
0	0.1	0.9	6228	12522	83.69	24	1	2	4
0	0	1	4375	12284	82.68	16	1	2	1

3.3 CONCLUSION

Both the thermal-based and simulation-based multi-objective mathematical models presented above allow explicitly for simultaneous consideration of all available combinations of alternative retrofit actions. They also allow for the consideration of logical, physical and technical constraints. Like any other multi-objective optimization problem, the search space, and therefore the set of non-dominated solutions, depends on the alternative retrofit actions considered and the constraints that may be imposed to allow their combination.

The result of the application of Tchebycheff programming, which has been employed for the analysis of the models under study, shows the feasibility of this methodology to find well balanced strategies for retrofitting of buildings to be presented to a DM in the framework of a decision support process.

However, the thermal-based model is not able to perform a detailed analysis of the building. Therefore, it does not allow for consideration of all desired objective functions such as thermal comfort. Moreover, this thermal code is developed for residential buildings, so application of the model for other types of building is not adequate.

Simulation-based model solved the above mentioned problems by using TRNSYS as building simulation and retrofit assessment engine.

However, the further consideration of all the possibilities that the DM has available for building retrofit (e.g., HVAC systems and renewable energy sources), as well as all the objectives that he/she may wish to optimize (CO_2 emission, social objective, etc.) may lead to a combinatorial explosion of the decision space, thus making the solving procedure extremely difficult and time-consuming.

In this case, other optimization techniques, namely evolutionary multi-objective algorithms may become necessary for tackling the problem. Besides, using approximation methodologies like neural network modelling of the building in the optimization part would be of interest.

CHAPTER 4
MULTI-OBJECTIVE OPTIMIZATION OF A SCHOOL BUILDING USING THE GAINN APPROACH

Summary:

What are the main advantages of the GAINN approach in comparison with previous methodologies?

What is the main framework for the proposed approach based on the GAINN methodology?

What are the main results from the implementation of the proposed approach on the case study?

Chapter 4: Multi-objective Optimization of a school building using the GAINN approach

This chapter presents a multi-objective optimization model based on the GAINN (Genetic Algorithm Integrating Neural Network) to quantitatively assess technology choices in a building retrofit project. This model combines the rapidity of evaluation of Artificial Neural Network (ANN) with the optimization power of GA. The benefits of this combined approach with respect to the classical optimization models previously presented (Chapter 3) are its rapidity and computational efficiency.

This model is able to take into account all feasible combinations of choices, without being confined to a small set of predefined scenarios in building retrofit. A school building is used as a case study to demonstrate the practicability of the proposed approach and highlight potential problems that may arise. A wide decision space is considered, including alternative materials for the external walls insulation, roof insulation, different window types, and solar collectors, as in previous chapter, but also HVAC system. The study starts with the single objective optimization of energy consumption, retrofit cost, and thermal discomfort hours. It then moves to multi-objective optimization. The single objective analysis focusses on the building's characteristics and performance; whereas the multi-objective analyses are concerned with the interaction between different objectives, and assessing their trade-offs.

4.1 Description of the optimization approach

The optimization framework of this step is summarized in Figure 4-1. It is divided in three sequential steps. First, a model of the existing building is created in TRNSYS and validated using utility bills. Then, using this model, a database of simulation cases is created and used to train and validate the ANN. After training and validation, the ANN is able to perform fast evaluations of the building performance, with a good accuracy and without oversimplifying the problem. Finally, a multi-objective genetic algorithm (MOGA) is run using the ANN to evaluate potential solutions.

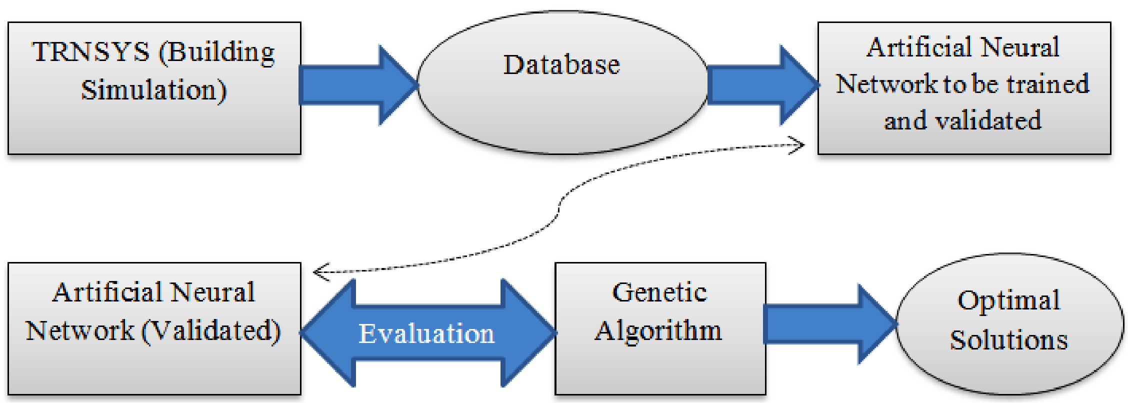

Figure 4-1 Optimization framework (Magnier & Haghighat 2010)

Although not much exploited specially in building retrofit, the integration of an ANN within a genetic algorithm is not a new idea. GAINN was first used in building engineering for the optimization of chillers control (Chow et al. 2002). This study introduced the methodology to the building field, and proved its efficiency in terms of accuracy and reduction of the total optimization time. Later, GAINN has been successfully applied in other studies, such as Zhou (2007), combined with computational fluids dynamics to aid ventilation system design and operation in an office apace, with the goal of achieving satisfactory thermal comfort and IAQ with minimum energy cost. Conraud (2008) used GAINN combined with the simulation program ESP-r to assess the optimal configuration for a building in terms of energy and indoor environment performance. These studies confirmed that numerical optimization using a combination of an ANN and a GA can be efficient for building applications, which can save a significant amount of computation time. However, all of these studies were based on an aggregative handling of multiple objectives (i.e., the objectives are aggregated into a single function to be optimized) and did not fully exploit the GAINN methodology (Magnier 2008).

Recently GAINN was used by Magnier et al. (2010) using a simulation-based ANN to characterize building behavior, and then the ANN model was combined with a multi-objective GA to optimize thermal comfort and energy consumption in a residential building design.

In this phase of the thesis, the GAINN methodology is used to quantitatively assess technology choices in a building retrofit project. This approach is used to explore the trade-offs between energy consumption, retrofit cost and thermal discomfort hours for a typical school building in Portugal.

The remainder of this chapter is organized as follows. The modules in the proposed approach are discussed in detail in this section. The application of the model to the retrofit of a school building is described in section 4.2. Finally, section 4.3 summarizes conclusions and limitations of this approach.

4.1.1 Building simulation

The building is simulated using TRNSYS (version 16) software. The "Multi-zone Building" Type 56 of TRNSYS is used to simulate the thermal behavior of the building. Due to the complexity of a multi-zone building the parameters of Type 56 are not defined directly in TRNSYS input file. Instead, a so-called building file (*.bui) is assigned containing the required information (TRNSYS 2009).

4.1.2 Parametric runs

In order to create a database for ANN training, parametric runs have to be executed. In order to automate TRNSYS runs, GenOpt (version 3.0.3) (2009) is used.

GenOpt is an optimization program for the minimization of a cost function that is evaluated by an external simulation program. When associated with TRNSYS, GenOpt can automatically generate building (.bui) and deck (.dck) files based on the chosen templates, run TRNSYS with those files, save results and restart again.

By using GenOpt, there is no need to write all deck and building files by hand, and therefore a significant amount of time is saved. More importantly, the risk of mistakes while writing the files is significantly lowered.

4.1.3 Design of experiments

In order to reduce the size of the training database while keeping the sample representative, Latin Hypercube Sampling (LHS) is used. LHS is one of the most common methods used to generate a small and representative sample of a population, for specified numbers and ranges of variables. Studies have shown that using LHS, a number of cases greater than twice the number of parameters is sufficient to correctly sample the search space (McKay 1988).

The principle of LHS is simple and can be illustrated as in Figure 4-2. For a 2-variable problem with a search space conceptualized as a square, the LHS method takes one and only one point per each column and per each row. The complete sample is therefore relatively small but remains representative of the whole search space. In this study, LHS is computed in MATLAB, using the Model-Based Calibration Toolbox (version 4.1). The Space-filling design style with LHS sampling designs from MATLAB Design Editor in the Model-Based calibration toolbox is used to create the experiment.

	Variable A			
Variable B			X	
				X
		X		
	X			

Figure 4-2 Illustration of LHS for a 2-variable problem

4.1.4 Artificial neural network

ANNs are information processing systems that are non-algorithmic, non-digital, and intensely parallel (Caudill & Butler 1993). They learn the relationship between the input and output variables by studying previously recorded data. An ANN resembles the biological neural system, composed by layers of parallel elemental units, called neurons. The neurons are connected by a large number of weighted links, over which signals or information can pass. Basically, a neuron receives inputs over its incoming connections, combines the inputs, performs generally a non-linear operation, and then outputs the final results. The most known, simple and used network arrangement is the feed-forward model. In this model, the neurons are placed in several layers. The first one is the input layer, which receives inputs from outside. The last layer, called output layer, supplies the result evaluated by the network. Between these two layers, a network can have none, one or more intermediate layers called hidden layers.

Figure 4-3 shows a three-layer feed-forward neural network with input, hidden, and output layers, which is the model used in this thesis. Each node in the input layer represents the value of one independent variable while the output nodes indicate the dependent variables.

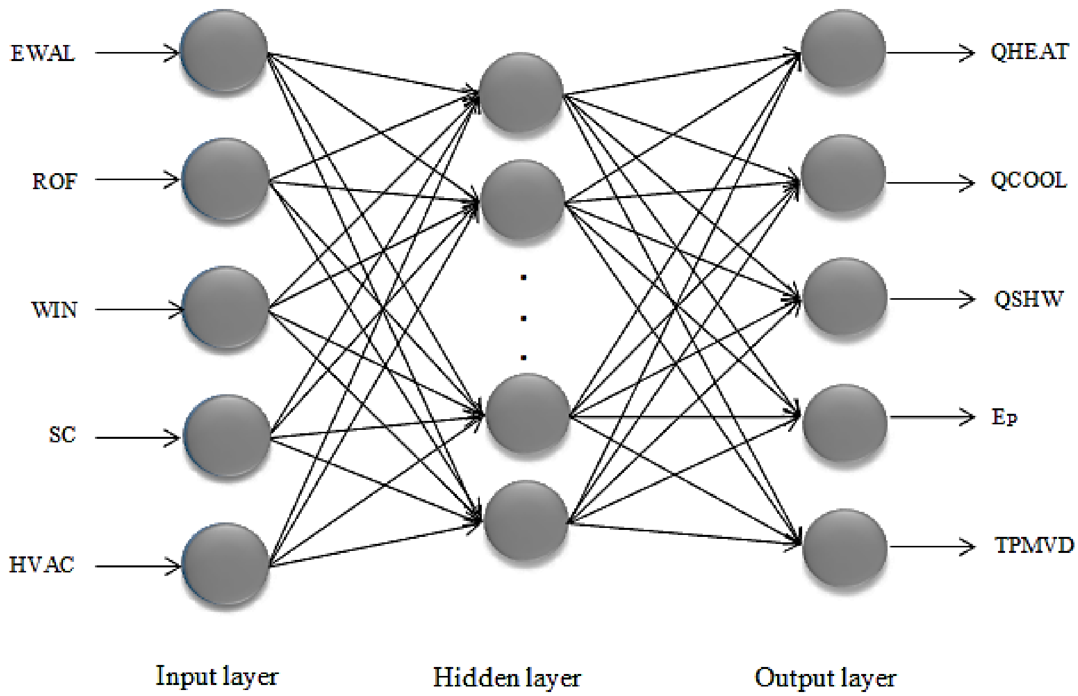

Figure 4-3 ANN architecture

MATLAB computing environment is chosen to generate the neural network model from the data using the neural network toolbox (version 7.0). It will be trained using a first sample from LHS, and checked for validation using a second and smaller sample.

4.1.5 Multi-objective optimization

Simultaneous optimization of energy consumption, retrofit cost and thermal discomfort hours falls in the ambit of multi-objective optimization. There is no unique solution to this multi-objective optimization problem, but a set of non-dominated solution or Pareto optimal solutions. This multi-objective problem is of combinatorial nature because of its structure and decisions to be made, and it is nonlinear due to the building energy and comfort calculations. Therefore, a multi-objective genetic algorithm (MOGA) is selected to characterize the Pareto optimal (non-dominated) front in this thesis.

Once trained and validated, the ANN will be used as the evaluation function for energy consumption and thermal discomfort estimation within the MOGA. The GA toolbox (version 5.1) in MATLAB is used for optimization using the ‘gamultiobj’ function to identify the set of non-dominated solutions.

MATLAB’s ‘gamultiobj’ function uses a controlled elitist GA (a variant of NSGA-II (Deb 2001)). Like any other GA, this is based on the evolution of a population of individuals, each of which is a solution to the optimization problem. In this work, an individual represents the result of a retrofit project carried out on a building. To use a genetic analogy, each individual is represented by a chromosome whose genes correspond to a number of the individual’s characteristics, as in Figure 4-4.

An elitist GA always favours individuals with better fitness value (rank). A controlled elitist GA also favours individuals that can help increase the diversity of the population even if they have a lower fitness value. It assigns a fitness level and ranks individuals in the objective function space on the basis of the degree of non-dominance or dominance depth. The elitist selection mechanism emphasizes current best solutions in subsequent generations without applying any operators to them. Controlled elitism therefore maintains a balance between exploitation and exploration of the objective function space (Srinivas & Deb 1994).

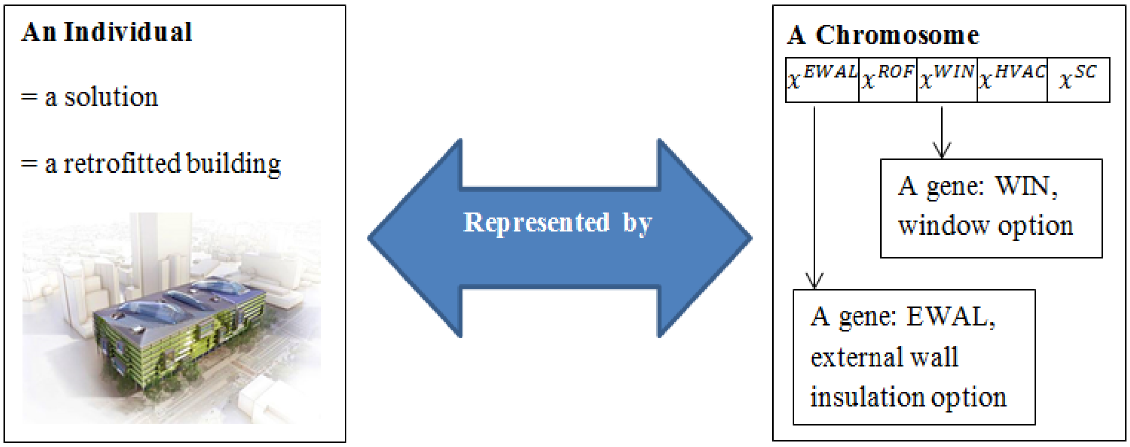

Figure 4-4 A solution to an optimization problem, as presented by a chromosome

4.1.6 Decision variables

The decision variables reflect the total set of alternative measures that are available for retrofitting of a building (e.g. windows, insulation materials, etc.). The set of retrofit actions in this step concerns combinations of choices regarding external wall insulation material, roof insulation material, windows, installation of solar collector and different HVAC systems to the existing building. Therefore, five types of decision variables are defined concerning the alternative choices regarding:

- the external wall insulation materials;
- the roof insulation materials;
- the windows type;
- the solar collectors type;
- the HVAC systems.

For simplicity, it is assumed that only one retrofit action from each five sets of actions may be selected for the building retrofit.

Assuming availability of *I* alternative types of external wall insulation material, *J* alternative types of roof insulation material, *K* alternative types of windows, *L* alternative types of solar collector, and M alternative types of HVAC system, integer decision variables x^{EWAL}, x^{ROF}, x^{WIN}, x^{SC}, and x^{HVAC} are defined as follows:

$$x^{EWAL}: external\ wall\ insulation\ material\ type\ identifier \tag{4.1}$$

$$x^{ROF}: roof\ insulation\ material\ type\ identifier \tag{4.2}$$

$$x^{WIN}: window\ type\ identifier \tag{4.3}$$

$$x^{SC}: solar\ collector\ type\ identifier \tag{4.4}$$

$$x^{HVAC}: HVAC\ system\ type\ identifier \tag{4.5}$$

A list of alternative retrofit actions applied in this study is based on a CYPE rehabilitation price generator database (CYPEingenieros 2010) and presented in Appendix B.3. This list includes 24 different external wall insulation materials, 18 roof insulation materials, 3 windows types, 4 solar collector and 4 HVAC systems.

4.1.7 Objective functions

4.1.7.1 Energy consumption

The energy consumption of the building will be directly assessed by TRNSYS. The total energy consumption, EC, consists in energy consumption for space heating (QHEAT), space cooling (QCOOL) and sanitary hot water (QSHW) systems. SHW production by solar collector (QSC) is subtracted from the total energy consumption. Moreover, energy consumption for lighting is not included because this is not expected to significantly change as a result of the implementation of the considered retrofit actions. After training the neural network model, the MOGA uses the ANN model to calculate energy consumption.

4.1.7.2 Retrofit cost

The overall investment cost for the building retrofit ReCost(*X*) (*X* denotes the vector of all decision variables defined in section 4.1.6) is calculated by adding individual retrofit action costs as follows:

$$ReCost(X) = A_{EWAL}.C^{EWAL}(X) + A_{ROF}.C^{ROF}(X) + A_{WIN}.C^{WIN}(X) + C^{SC}(X) + C^{HVAC}(X) \quad (4.6)$$

Where:

A_{EWAL} – exterior wall surface area [m^2];

C^{EWAL} - cost in [€/m^2] for selected external wall insulation material;

A_{ROF} - roof surface area [m^2];

C^{ROF}- cost in [€/m^2] for selected roof insulation material;

A_{WIN} - windows surface area [m^2];

C^{WIN}– cost in [€/m^2] for selected window;

C^{SC}- cost for selected solar collector [€];

C^{HVAC}- cost for selected HVAC system [€].

The RAs corresponding costs ($C^{EWAL}, C^{ROF}, C^{WIN}, C^{SC}, C^{HVAC}$) are extracted from RAs characteristics tables presented in Appendix B.3. A MATLAB function using expression 4.6 is written and incorporated in MOGA to estimate retrofit cost objective function.

4.1.7.3 Total percentage of discomfort hours (TPMVD)

As mentioned in chapter 3, an absolute value of 0.7 for PMV, the upper limit of the less exigent comfort category in ISO 7730, is considered as the borderline of the comfort zone. Therefore, in order to maximize the thermal comfort, the total percentage of cumulative time with discomfort (|PMV| >0.7) over the whole year during the occupancy period, TPMVD(X), should be minimized. The total percentage of discomfort hours is also predicted by TRNSYS. After training the neural network model, the MOGA uses the ANN model to estimate TPMVD.

4.2 MODEL APPLICATION ON A SCHOOL BUILDING

The case study was chosen on the basis of four criteria:

- Potential to influence energy savings on a national level;
- Geographical accessibility (proximity to Coimbra, Portugal);
- Cooperative building managers;
- Availability of building drawings and documentation.

Regarding the first criterion, it should be noted that commercial buildings are most suitable for achieving the market’s penetration of innovative and effective retrofit solutions to improve energy efficiency and implement renewables, with moderate additional costs. With their help it will be easier to reach groups of differing age and social origin. Commercial buildings can also be used as drivers to heighten awareness and sensitize society on energy conservation. Furthermore, there is an on-going national modernization program for the public network of secondary school buildings in Portugal that aims to retrofit and modernize these buildings, open the schools to the communities, and establish a new management model for school premises. All these items make school buildings a unique case study in this project.

The public secondary school network in Portugal as it is today consists of 502 schools, the construction of which began in the late 19th century. Based on the time of construction and architectural quality, one can divide the schools into three periods or phases: 1) up to 1935 (2%); 2) from 1935 to 1968 (21%); and 3) from 1968 until the present (77%) (ParqueEscolar 2009).

The Quinta das Flores secondary school (ESQF) building is selected as a case study to assess the practicability of the proposed approach and highlight potential problems that may arise. The ESQF building was constructed in 1983, that is in the third period of school building construction in Portugal, which represent 77% of the public Portuguese secondary school buildings. Therefore, this building represents a large number of Portuguese school buildings and the proposed model could be easily adopted by other similar cases.

4.2.1 General building description

The ESQF building is located in Coimbra, Portugal (Latitude: 40° 20ˈ N; Longitude: 8°, 41ˈ W) and serves some 800 students and 117 staff. The building consists of 6 blocks, the main block designed for administration purposes. 4 blocks (A, B, C and D), include classrooms and laboratories (Figure 4-5to Figure 4-9). These four blocks have similar architecture, with different number of storeys. Blocks A and D have three storeys and blocks B and C have 2 storeys. The last block is the sport pavilion. Besides this pavilion for sport activities, there are 3 uncovered spaces for this purpose. Total occupied space floor area is 9,850 m^2 and is divided between the 6 mentioned blocks.

In this project we study block A, one of the four identical blocks (Class rooms). The central zone in this block is a big atrium with visibility to all other sections in the building. This central zone uses natural lighting.

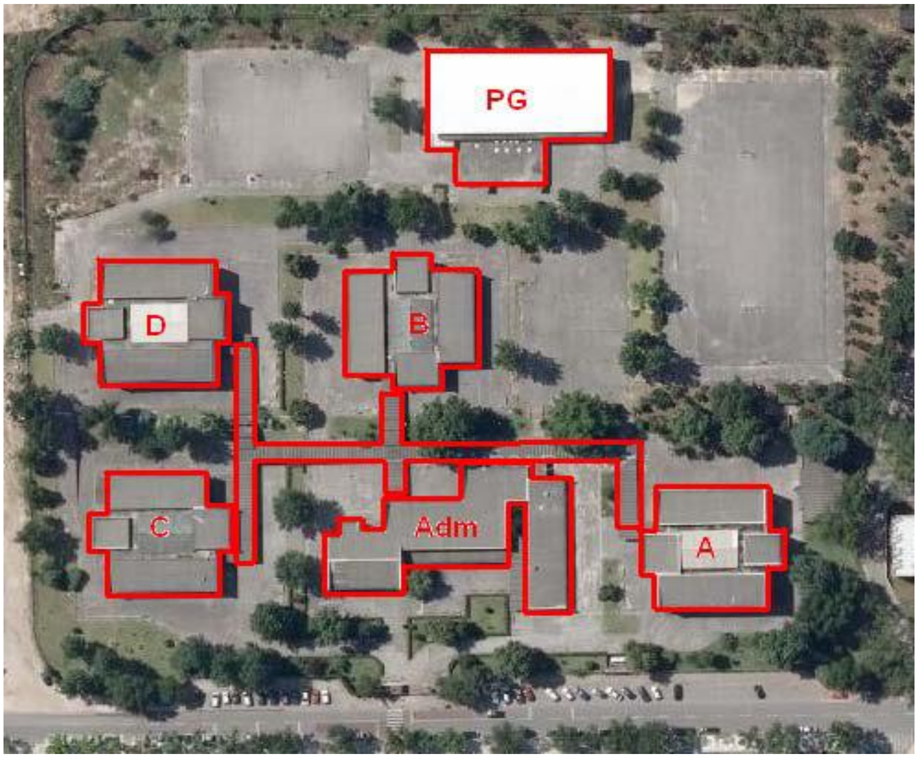

Figure 4-5 Building identification

Data was collected to describe the pre-retrofit energy use and thermal comfort in the building prior to assessing retrofits for the ESQF School. Information was gathered on heating, cooling, ventilation, lighting, and sanitary hot water use. Utility bills were also collected. The resources for collecting this information included as-built documents, Parque Escolar documents, site visits, monthly utility billing, and typical practice. Due to the on-going major retrofit on the building detailed measurements were not possible to perform.

Figure 4-6 Block A

Figure 4-7 Block B

Figure 4-8 Block C

Figure 4-9 Block D

Figure 4-10 illustrates the ground floor for Block A. six class rooms (A1-A6) are located in this floor, besides bathroom and three storage rooms. There are nine class rooms in the first floor of Block A, as well as one bathroom and one laboratory (Figure 4-11). In the second floor, there are eight more class rooms and two storage rooms (Figure 4-12).

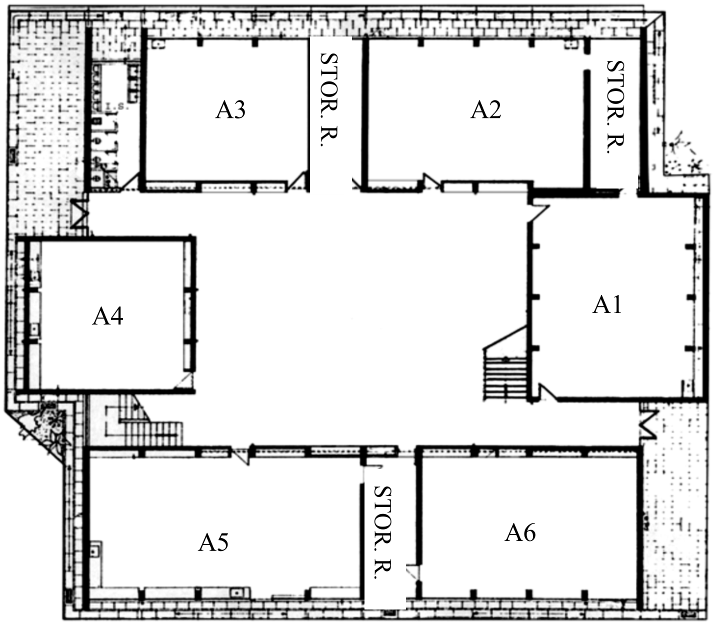

Figure 4-10 Block A ground floor plant

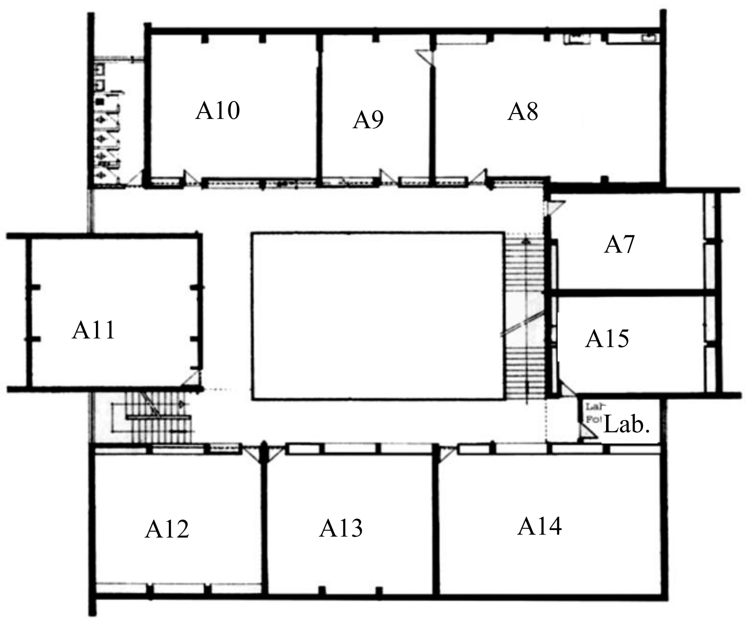

Figure 4-11 Block A first floor plant

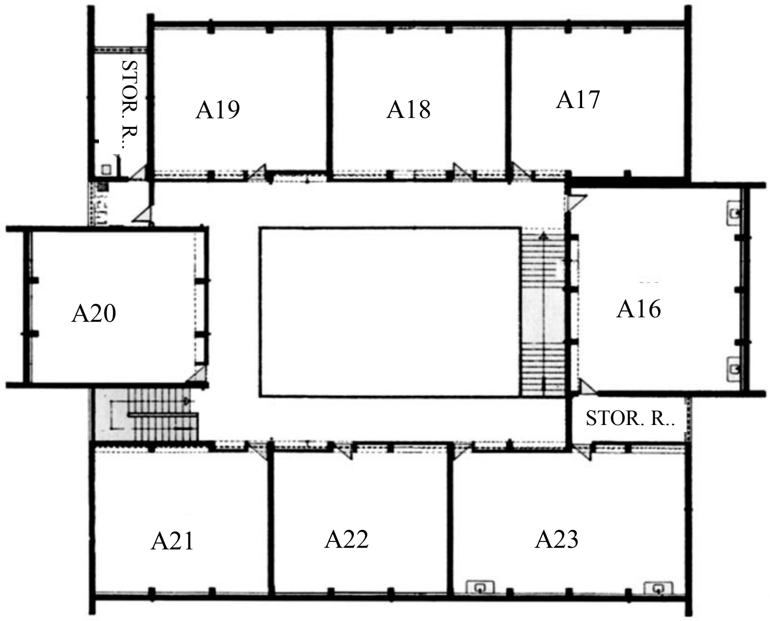

Figure 4-12 Block A second floor plant

Heating is supplied locally in each room by electric resistance radiators; the building has no cooling system. Monthly data on electricity consumption was available from the electricity supplier company from 2008 through 2010.

The school is three stories high. As-built documents indicate floor heights between 2.85m and 3.20m in the building. The utility floor area is the total floor area confined by the walls of the building and is equal to 1,886 m^2. The conditioned floor area is the total floor area that is heated and is equal to 1,622m^2.

As-built documents indicate that the density of windows is equal on three façades; 65% of the building's North, West and East façade. For the South façade it is 59%. All the windows are single glazed and 2.7m high by 2.0m wide (area of 5.4 m^2) with aluminium framing. Windows distribution on each wall is presented in Table 4—1.

Table 4—1Windows distribution between North, East, South, and West façades on the ground, 1st and 2nd floors

Building Façade	Floor	Number of Windows per Floor	Area per Window [m^2]	Window Area per Façade [m^2]	Window-Wall Ratio [%]
North Wall	Ground Floor, 1st, 2nd	10	5.4	54	65
South Wall	Ground Floor, 1st, 2nd	9	5.4	49	59
East Wall	Ground Floor, 1st, 2nd	3	5.4	17	65
West Wall	Ground Floor, 1st, 2nd	4	5.4	22	65
Total glazed area		26	5.4	140.4	-

The interior of the building is partitioned into different zones, based on the room use, occupancy pattern and orientation. This result in five building zones: North zone, East zone, South zone, West zone, and Atrium zone. A brief description of each zone is provided in Table 4—2.

Table 4—2 Building zone description

Building Zone	Description and Use	Utility Floor Area [m^2]	Conditioned Floor Area [m^2]	Zone Volume [m^3]
North zone	Class room	204.82	204.82	1894.59
East zone	Class room	58.25	58.25	538.8
South zone	Class room	202.16	202.16	1869.98
West zone	Class room	75.54	75.54	698.76
Atrium	Not occupied, no heating	264.1	-	2442.9

The structural materials in the ESQF School are brick and concrete. There is no insulation. Additional materials are used in wall, roof, ground, and window constructions.

A summary of the materials and properties used in the walls, roofs, and floors in the ESQF School is given in Table 4—3.

Table 4—3 Material properties of walls, roof, and floors of the ESQF School

		Conductivity (k) [kJ/hr.m.K]	Density (r) [kg/m^3]
Structural	Brick	3.2	1,800
	Concrete	7.56	2,400
Other	Gypsum	0.756	1,200
	Bitumen	0.61	1,100
	Plaster	5	2,000
	Cement	5.04	2,000
	Ceramic tile	4.32	2,000

	Resistance, R [m^{2}K/W]
Wall Air Space	0.132

Combinations of materials listed in Table 4—3 were used to define wall, roof, and floor constructions in the ESQF School.

The basic design is the same for all exterior wall constructions: plaster exterior with brick, air gap, brick and plaster interior. The wall construction is described in Table 4—4, including the materials, U-Value, and location of each construction. Constructions are defined from the interior building surface to the exterior building surface.

The roof construction is described in Table 4—5. The roof construction in atrium is different from all other zones. The atrium is covered by translucent polycarbonate, while the other zones roof is composed of plaster, concrete, bitumen, and cement.

Table 4—4 External wall structure

Exterior Wall Constructions	All walls
Interior Surface Layer	2 cm Plaster
Layer #2	11 cm Brick
Layer #3	4 cm Air Space
Layer #4	11 cm Brick
Exterior Surface Layer	2 cm Plaster
U-Value [W/m^{2}K]	1.737

Table 4—5 Roof structure

Roof Constructions	
Interior Surface Layer	2 cm Plaster
Layer #2	22 cm Concrete
Layer #3	1 cm Bitumen
Layer #4	4 cm Cement
U-Value [W/m^{2}K]	2.654

4.2.2 Building simulation

Table 4—6 presents summary of the set-up for the existing building according to the information discussed in the previous section. Based on this table, a building model is developed in TRNSYS. A schematic view of the model is shown in Figure 4-13.

The type-56 multi-zone building is a reproduction of the reference building (Figure 4-14). The building model is divided into 5 zones: North zone, East zone, South zone, West zone, and Atrium zone. Heating is supplied locally in each room by electric resistance radiators; the buildings have no cooling system. The atrium is not heated or cooled.

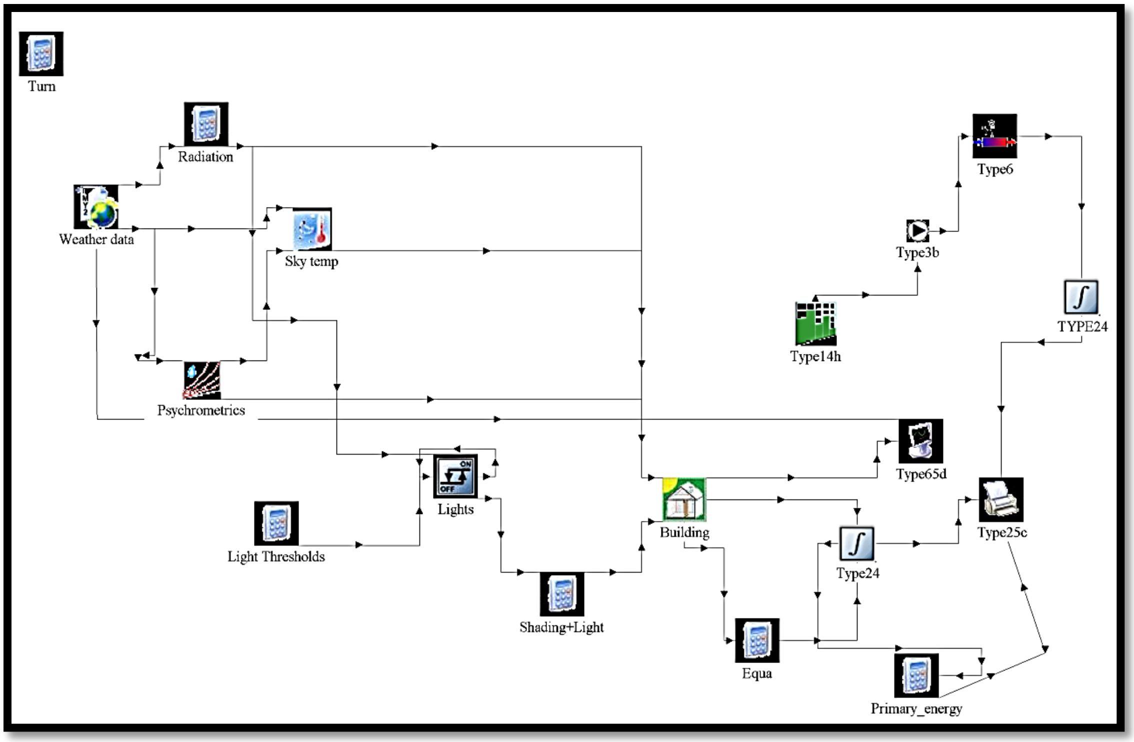

Figure 4-13 TRNSYS model view

In order to validate the TRNSYS model, simulation results have been compared with utility bills data. The TRNSYS model was run using the existing building parameters described earlier, with one hour time step, using DOE typical meteorological year version 2 (TMY2) weather data.

Table 4—6 Brief description of the base building parameters for simulation

Location		Coimbra, Portugal
Building type		School building
Floor areas	utility floor area	1,886 [m^2]
	conditioned floor area	1,622 [m^2]
Dimension and Heights	Average floor height	3.02 [m]
	Window height	2.7 [m]
	Window-to-wall ratio	65% , except South façade 59%
Construction of building envelope	External walls	2cm plaster + 11 cm Brick + 4cm air space + 11 cm brick + 2 cm plaster (U-value = 1.737 W/m^2K)
	Roof	2cm plaster + 22cm concrete + 1cm bitumen + 4 cm cement (U-value = 2.654 W/m^2K)
	Windows	Single-pane simple glass (U-value = 5.68 W/m^2K, g-value = 0.855)
Operating hours	Monday to Friday	8:00 – 20:00
	Weekend	Closed
HVAC parameters	Total number of persons	200
	Lighting + Equipment	Lighting 10 W/m^2, Equipment 12 W/m^2
	Infiltration rate	0.9 ACH
	Cooling system	None
	Heating System	electric resistance radiators
	Thermal set points	20˚C – No max.

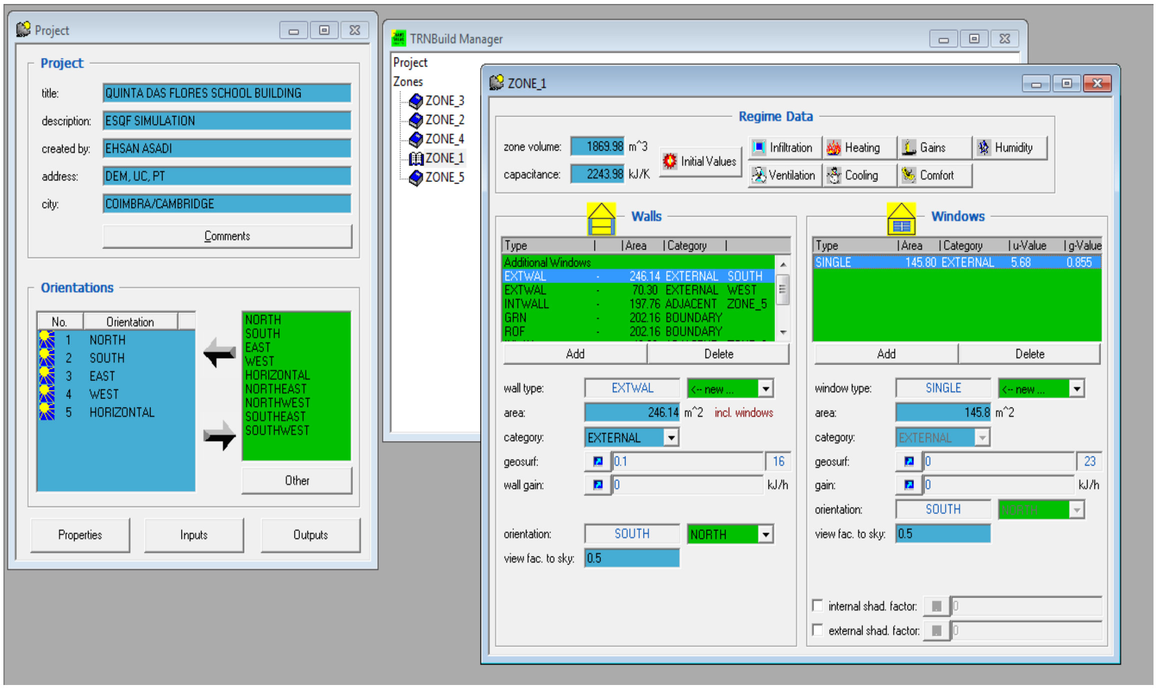

Figure 4-14 Screenshot of the type-56

Figure 4-15 displays the cumulative monthly energy consumption for the whole year. The total energy consumption of the ESQF school building is 44.2 [kWh/m^{2}year] from utility bill analysis and 47.2 [kWh/m^{2}year] based on the simulation result. The simulated results are reasonably close to utility bills data. The mean absolute deviation between simulated and utility bill energy consumption is 10%. The major sources of uncertainties in the detailed model predictions are related to proper consideration of lighting, equipment, occupancy schedules and weather data.

In Figure 4-15, there is a black line representing the simulation result including cooling needs, besides heating and SHW consumptions. As it was mentioned earlier, there is no cooling system in the existing building. However, some of the retrofit actions considered regarding the HVAC system will also include cooling systems. Therefore, an estimation of cooling needs is required. This has been taken into account by estimating cooling needs considering the recommended set point for cooling according to Portuguese national regulation RSECE which is equal to 25˚C (RSECE 2006).

	Jan	Feb	March	April	May	June	July	August	Sep	Oct	Nov	Dec
Simulation (Heating+Cooling+DHW)	18.25	31.70	40.68	46.00	48.89	53.30	62.26	71.35	78.10	82.21	92.28	109.56
Simulation (Heating+DHW)	18.06	31.27	39.75	44.82	47.07	47.42	47.77	48.12	48.46	49.83	59.46	76.65
Utility bill 2008	17.12	30.23	38.08	42.13	41.90	46.23	42.95	47.26	46.91	47.09	58.69	71.67

Figure 4-15 Simulated and measured cumulative monthly energy consumption

4.2.3 Artificial neural network approach

As mentioned before, MATLAB Neural Network toolbox is used to train and develop the neural network model for simulating the building energy consumption and thermal discomfort.

In General designing an ANN model follows three steps:

- Design of experiments including collecting and pre-processing the data;
- Building the network, and train the ANN model;

- Validate the model and test the model performance.

4.2.3.1 Parametric runs

A sample of 950 cases was used for ANN training. This sample was created by LHS, based on the decision variables (retrofit actions). All the cases have been simulated with TRNSYS, using GenOpt capability for automatic parametric runs.

Simulations were performed with 1 hour time step. The total simulation time of the 950 cases took around 3 days (5.19 minutes for each simulation) using an Intel Core2 Duo CPU workstation at 2.66 GHz speed.

4.2.3.2 Artificial neural network training

A three-layer neural network (including Input, Hidden and Output layers) using sigmoid transfer functions for the first layer and linear functions for the second layer is generally able to approximate any function having a finite number of discontinuities, given sufficient neurons in the hidden layer (Mathworks 2010). The ANN model adopted in this study was composed of one input layer representing the 5 decision variables (different retrofit action types, i.e. EWAL, ROF, WIN, SC, and HVAC), one hidden layer composed of 15 neurons, and one output layer composed of the four energy consumption and one thermal comfort variables (QHEAT, QCOOL, QSHW, E_P, and TPMVD) (Figure 4-3). Selection of the optimal number of hidden layer neurons in the ANN architecture falls in the rubric of bias-variance dilemma. Bias indicates the degree of agreement between the model and the training data whereas variance represents the complexity of the approximating model. The number of hidden neurons determines the model complexity of an ANN. Increasing the number of hidden layer neurons compromises the generalization ability of the ANN at the cost of minimizing the training data set error. The number of neurons in the hidden layer, in this study, was found by trial-and-error. A schematic diagram of the basic architecture is shown in Figure 4-16. Transfer functions used are hyperbolic tangent sigmoid functions in the initial and hidden layers, and linear functions in the output layer. The method used for the ANN training is back-propagation, associated with Levenberg-Marquardt and Bayesian regularization algorithms. All inputs and outputs were scaled to the [-1,1] range prior to training to enable a better efficiency as recommended in MATLAB (Mathworks 2010).

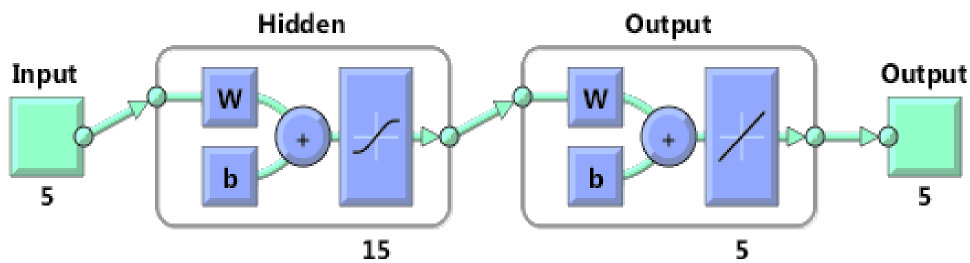

Figure 4-16 Construction of the ANN model

The ANN was trained with 950 cases. The training was considered to have reached convergence if the root mean square errors (RMSE) stabilized over a certain number of iterations (as shown in Figure 4-17). It is worth noting that the RMSE is a measure of how close the ANN predicted profile is to the one based on simulation results. The ANN training reached this goal after 150 epochs[2], with a final RMSE of 0.0240. Regression correlation coefficients between the network outputs and the corresponding TRNSYS simulation outputs were found very close to 1 for the five outputs studied, demonstrating a very good correlation between outputs and target values. Figure 4-18 illustrates the regression for primary energy consumption and thermal discomfort indicator, TPMVD.

[2] Epochs: number of iterations applied for training

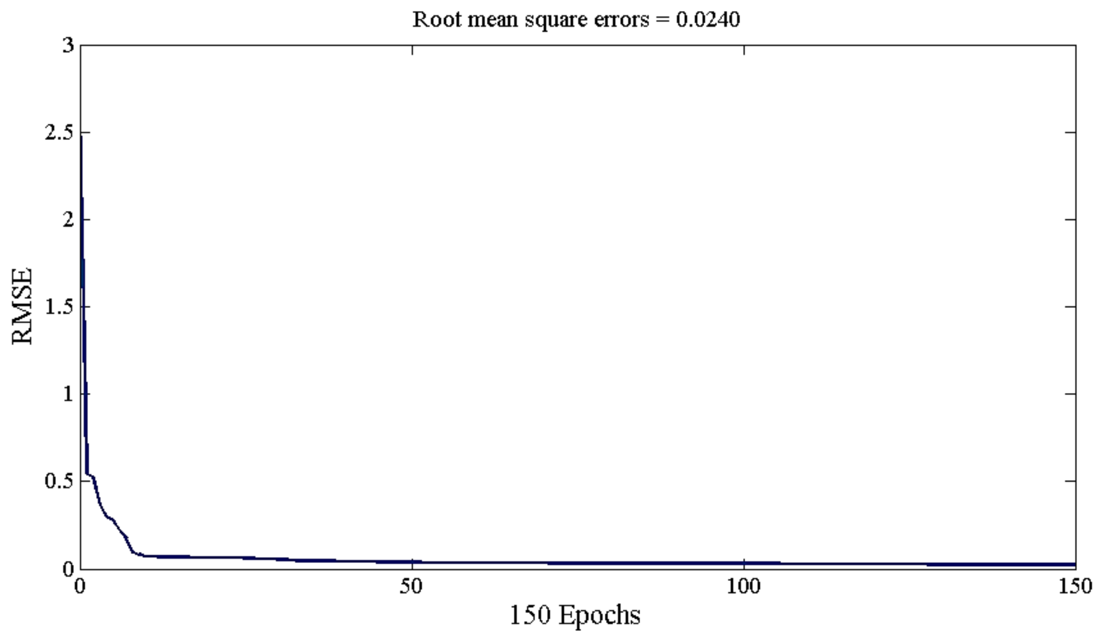

Figure 4-17 Convergence history of ANN training

4.2.3.3 Artificial neural network validation

A sample of 95 cases, different from the previous ones, was used for ANN validation. Figure 4-19 illustrates the relative error between ANN and TRNSYS outputs for primary energy and TPMVD outputs. Besides, the distribution of the relative errors for the five outputs is summarized in Table 4—7. The average relative errors regarding energy consumption outputs are good, with 1.4% for heating, 0.5% for cooling, 0.4% for sanitary hot water, and 0.9% for primary energy. Regarding the thermal discomfort output TPMVD, the average error is a bit higher but still acceptable, with 2.5% for TPMVD.

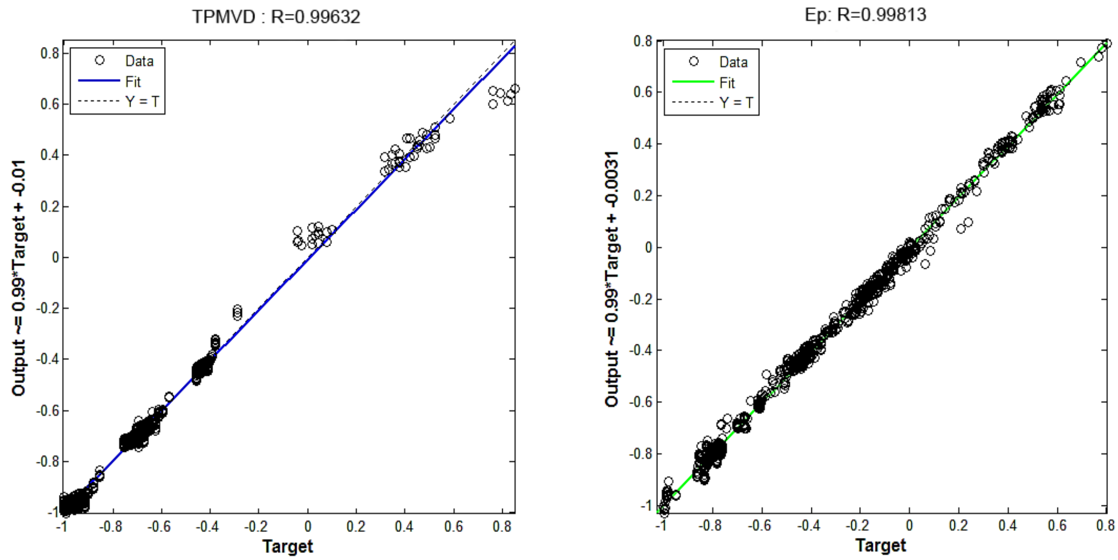

Figure 4-18 Linear regression of ANN predicted outputs (TPMVD, primary energy) on targets

Table 4—7 Statistical repartition of relative errors in ANN validation

Relative error		<1%	<2.5%	<5%	<10%	<25%	Average relative Error (%)
Percentage of cases when error falls into the range	QHEAT	47%	70%	89%	99%	100%	1.4
	QCOOL	92%	100%	100%	100%	100%	0.5
	QSHW	93%	100%	100%	100%	100%	0.4
	Ep	59%	95%	100%	100%	100%	0.9
	TPMVD	33%	60%	89%	98%	100%	2.5

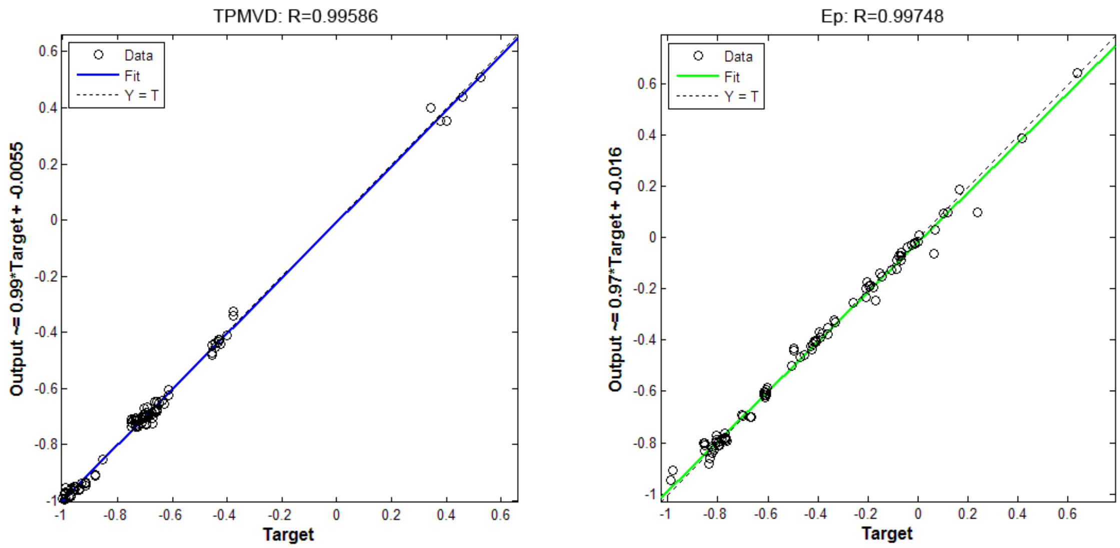

Figure 4-19 Linear regression of ANN predicting TPMVD and primary energy on targets

Reaching an acceptable ANN accuracy was a difficult task for the current case study. The number of neurons to set in hidden layers was one of the challenges of the model. Increasing the number of neurons in the hidden layers could on average improve ANN predictions, but it also increases the maximal error. This is caused by a phenomenon called over fitting, in which the ANN uses a high number of parameters to have a very high accuracy regarding the training data, at the cost of great variations between each training point. This behavior is dangerous in the current study since great variations could lead to false non-dominated solutions in the subsequent MOO. Based on the general idea that it is less risky for optimization to have small and frequent errors rather than rare but important ones the author decided to keep 15 neurons in the hidden layer.

On the whole, the author considers the ANN accuracy is acceptable, since the relative errors for energy consumptions are low and the relative error of 2.5% for TPMVD results in a very small variation in the TPMVD value.

4.2.4 GAINN optimization

The final goal of the optimization problem in this phase is the simultaneous optimization of energy consumption, retrofit cost, and total percentage of discomfort hours. GA is used to tackle this multi-objective optimization problem to identify the set of non-dominated solutions. A modified version of MATLAB's 'gamultiobj' function is used. The MOO problem can be summarized as follows, using integer decision variables stated in (4.1) – (4.5):

$$
\begin{gathered}
Min\, Z_1(X) = EC(X) \\
Min\, Z_2(X) = ReCost(X) \\
Min\, Z_3(X) = \; TPMVD(X) \\
S.t. \\
1 \leq x^{EWAL} \leq I, (I = 24) \\
1 \leq x^{ROF} \leq J, (J = 18) \\
1 \leq x^{WIN} \leq K, (K = 3) \\
1 \leq x^{SC} \leq L, (L = 4) \\
1 \leq x^{HVAC} \leq M, (M = 4)
\end{gathered}
\qquad (4.7)
$$

EC and TPMVD are calculated by the neural network, whereas ReCost is calculated by a MATLAB function written using expression (4.6). Moreover, a MATLAB function using an ANN model as the input was written for creating a fitness function for the MOGA. The upper bounds for the five decision variables are the maximum number of retrofit actions of each category. The algorithm options were set according to Table 4—8 using MATLAB's "gaoptimset" function:

Table 4—8 MOGA options values that are set using “gaoptimset” function (Mathworks 2010)

Option	Value
SelectionFcn	@selectionstochunif
MutationFcn	@mutationadaptfeasible
MigrationDirection	[‘forward’] with migration fraction set to 0.2
DistanceMeasureFcn	@distancecrowding
PopulationSize	200

After setting up the optimization variables and parameters, according to the above mentioned data, the results from the optimization are illustrated in Figure 4-20 to Figure 4-26. Three sets of optimizations were carried out. The first set focussed on single-objective optimization, the aim being to minimize the values of three objectives separately: energy consumption, retrofit cost, and thermal discomfort. The second set involved the multi-objective optimization of pairs of objectives, with the aim of understanding the interactions between objectives, and how much each could affect the building’s characteristics and performance. The third set involved the multi-objective optimization of all three objectives. The general aim was to find out how the results varied between the first two sets of optimizations and the last one, and to produce the visualization of the results that would be best suited to their analysis.

4.2.4.1 First set of optimization (single-objective)

The objective of these optimizations was to minimize the values of three objectives: energy consumption, retrofit cost, and total percentage of discomfort hours.

Single-objective minimization of Energy Consumption

Here, the goal was to minimize energy consumption for heating, cooling and SHW purposes. The results are given in Table 4—9 and Figure 4-20.

In the EC optimized building, the insulation level was high with thick layers of insulating material with lowest U-values for external wall and roof. In addition, window type 3, which has the lowest thermal transmittance, is selected. Regarding the HVAC system, an oil-based boiler without cooling option is recommended. Furthermore, the flat solar collector with highest area among all the systems considered is recommended. However, this set of retrofit actions resulted in a significant increase of the retrofit cost with respect to the ReCost optimized building.

Table 4—9 Results of single-objective optimization (Refer to Appendix B.3 for RAs characteristics)

Type of solution	EC [kWh/m^{2}year]	ReCost [k€]	TPMVD [%]	EWAL	ROF	WIN	HVAC	SC
[min] EC	***14.58***	100.840	27.61	16	18	3	1	2
[min] ReCost	37.82	***36.859***	60.24	1	7	1	1	3
[min] TPMVD	32.37	108.69	***16.70***	16	11	3	2	3

Single-objective minimization of retrofit cost

The results from this optimization are given in Table 4—9 and Figure 4-20. Minimizing retrofit cost resulted to low insulation level and single glazed window. Besides, the cheapest HVAC system (oil-based boiler without cooling system) and the cheapest solar collector have been recommended. However, this resulted in a significant increase of the energy consumption and thermal discomfort hours compared to the EC and TPMVD optimized buildings.

Single-objective minimization of total percentage of discomfort hours

Here the aim was to minimize the total percentage of thermal discomfort hours in the building. There is no cooling system in the existing building, either active or passive. The results from optimization are given in Table 4—9 and Figure 4-20.

Minimizing TPMVD resulted in high insulation level and double glazed windows, similarly to minimization of energy consumption. Regarding HVAC system, HVAC type 2 with natural gas boiler for heating and chiller for cooling was selected that led to significantly better indoor comfort compared to the existing building.

The results produced by this first set of optimization runs are given in Figure 4-20. Those for minimization of retrofit cost diverged significantly from the others. The solution that minimizes energy consumption and thermal discomfort were comparable, which is due to the nature of retrofit actions considered and objective functions. This figure can be used to shape the expectation of the DMs and help them to elicit appropriate constraints to objective function values for further considerations.

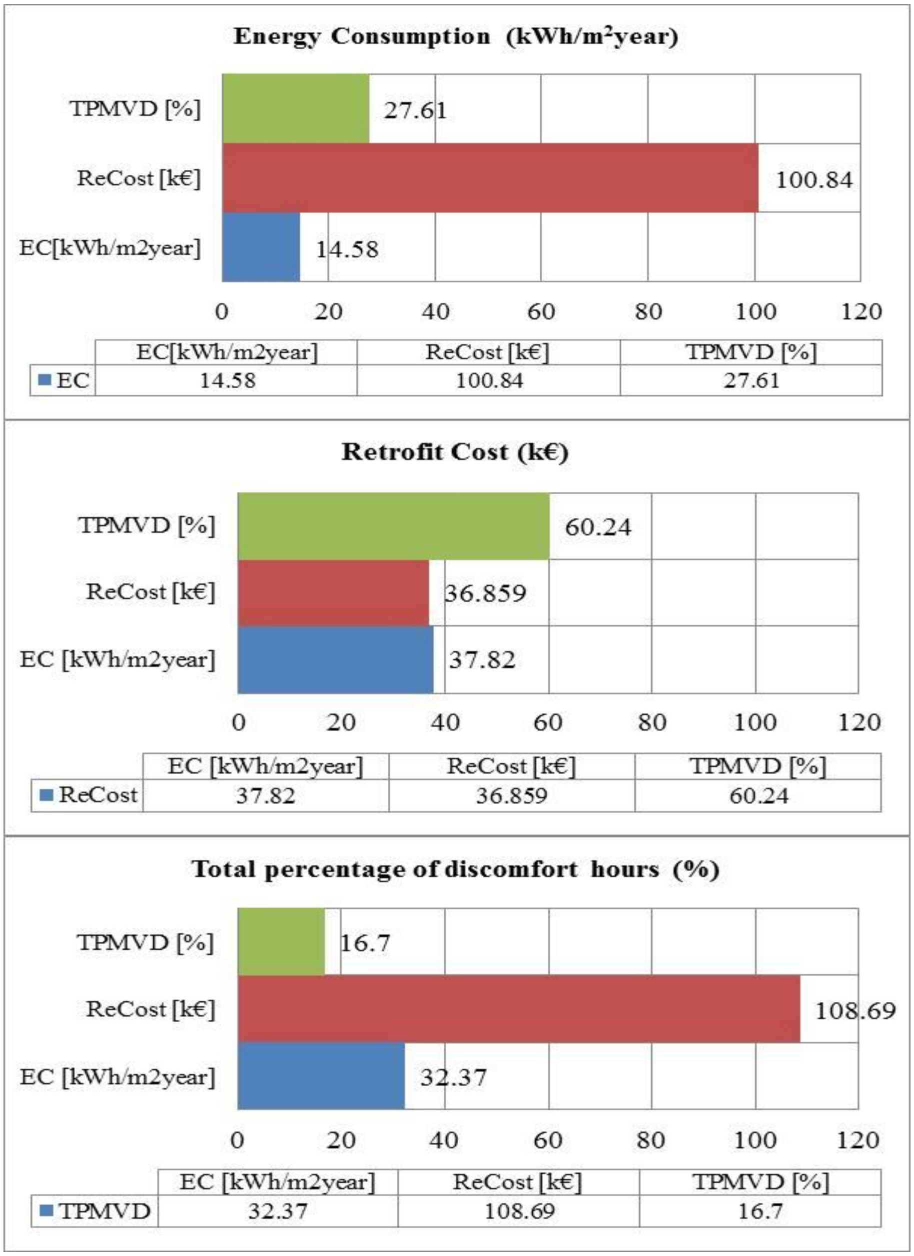

Figure 4-20 Results of single-objective optimization

In summary, the results produced by single-objective optimization unveiled some of the interaction between the different objectives. The second set of optimizations produced further information about these interactions.

4.2.4.2 Second set of optimization (two-objective)

In each of these multi-objective optimizations, two objectives were chosen from among energy consumption, retrofit cost, and total percentage of discomfort hours.

Multi-objective optimization of energy consumption and total percentage of discomfort hours

Here, the aim was to simultaneously minimize EC and TMPVD. The results are given in Figure 4-21. Each point on the Pareto front is associated with a set of decision variables that are retrofit actions.

The optimization process generated three solutions, which formed the Pareto front. The single-objective optimization results for EC and TPMVD were similar with one major difference which was the HVAC system. There were the same external wall insulation material and window type. The roof insulation material characteristic is also similar. And in the multi-objective optimization trials, there was a minimization of the energy consumption by changing HVAC system type from the system with cooling (HVAC = 2) to the system without cooling option (HVAC = 1).

The similarities between the single-objective results meant that there was little variation among the multi-objective results. It is worthwhile also to mention that the small number of non-dominated solutions is due to the fact that the lower EC values are mainly achieved with the HVAC system type 1 without cooling option (HVAC = 1) that lead to high TPMVD values. Therefore, a large number of potential solutions are dominated by the EC optimal solution. Moreover, since the optimization solver switched from Air Source Heat Pump (HVAC = 3) to the Oil-based boiler with no cooling option, a significant decrease in energy consumption resulted, explaining the large step at EC equal 28.52 [kWh/m^{2}year] in the Pareto front as exhibited in Figure 4-21.

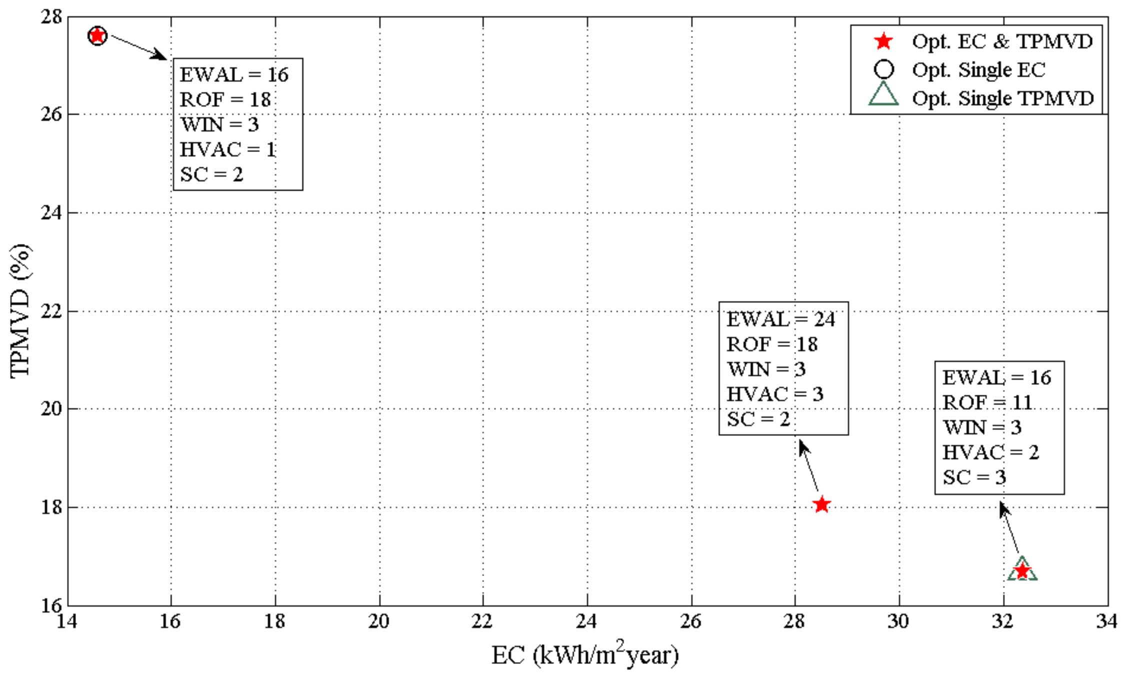

Figure 4-21 Multi-objective solutions for the building retrofit strategies (EC – TPMVD) (Refer to Appendix B.3 for RAs characteristics)

Multi-objective optimization of energy consumption and retrofit cost

The single-objective optimization would suggest that these objectives were mutually opposed. The results are given in Figure 4-22. There is a larger number of non-dominated solutions than in the case of EC and TPMVD.

Regarding the HVAC system the solutions are all similar, consisting of oil-based boiler without cooling option. None of the HVAC systems with cooling option is selected since this requires additional investment cost and energy consumption compared to the non-dominated solutions. This can be explained through the fact that there is no constraint on summer overheating (or TPMVD), therefore there is no reason for additional investment in a cooling option.

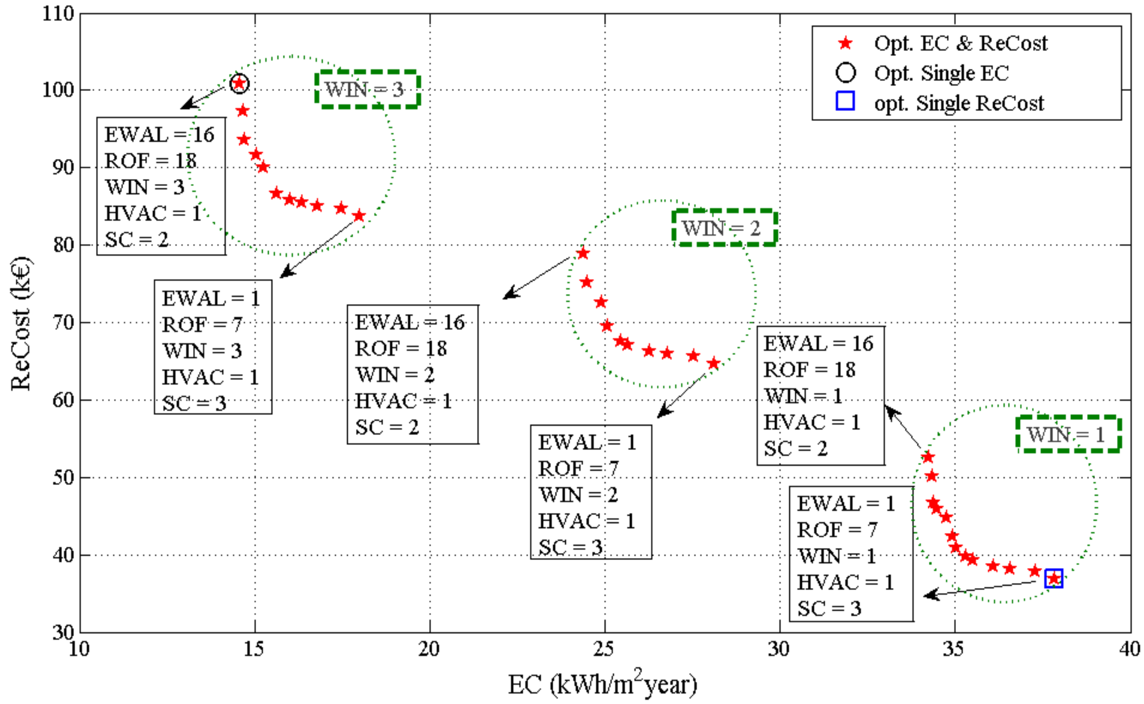

Figure 4-22 Multi-objective solutions for the building retrofit strategies (EC - ReCost) (Refer to Appendix B.3 for RAs characteristics)

Wall and roof insulation material as well as windows and solar collector systems vary in different non-dominated solutions. Also, it is worthwhile to mention that the obtained solutions on the Pareto front are found to be grouped according to the window types. This reveals that the window has a stronger influence on the low EC cost-effective solutions than the other decision variables.

To obtain minimum solutions of ReCost, single glazed window (WIN=1), the lowest price window, and the cheapest solar collector (SC=3), is found to be optimal with incrementally additional insulation compare to the exisitng building to lower the energy consumption. However, since the thickest insulation with lowest U-values for external wall and roof (EWAL= 16, ROF = 18), as well as the largest solar collector (SC=2) are selected, the optimization led to the double-glazed window (WIN=2). This leads to a significant reduction in the EC, explaining the dicontinuty (EC step) in the Pareto front at 34.24 kWh/m^{2}year of EC as illustrated in Figure 4-22. The same phenomena happen at the second step in the EC (EC = 24.38) in the Pareto front, where the optimization led to window type 3 with lowest U-value resulting to a significant reduction in the EC.

Multi-objective optimization of total percentage of discomfort hours and retrofit cost

The results of this optimization are given in Figure 4-23. The different non-dominated solution all fall between two single-objective optima.

Regarding the solar collector, all the recommended solutions are equal: the cheapest solar collector is recommended. All the other retrofit actions vary in different non-dominated solutions.

The optimization solver tried to minimize the TPMVD using optimal combinations between the building envelope parameters (including external wall and roof insulation materials, and window type) and the HVAC system type.

Double glazed window with lowest thermal transmittance, thick layer of insulation with low U-values for external wall insulation and roof, and the HVAC system type 2 with cooling option are selected giving the lowest TPMVD value. A cheaper HVAC system (HVAC = 3) is utilized to obtain a set of solutions which produce smaller amounts of ReCost without too much sacrificing thermal comfort. For more reduction in ReCost, HVAC system type 1 is used. Moreover, window type 2 then type 1 is selected to reduce the ReCost. There is a large discontinuity in the Pareto front at 38.62% of TPMVD. This can be explained by changing the HVAC type 3 to 1 with no cooling option. As can be seen, a relatively small amount of reduction in ReCost leads to a large reduction in thermal comfort. Therefore, in the current case, the DM could be convinced to slightly increase the amount of investment from 42 k€ to 50 k€ to improve the thermal comfort in the building by 20 percentage points.

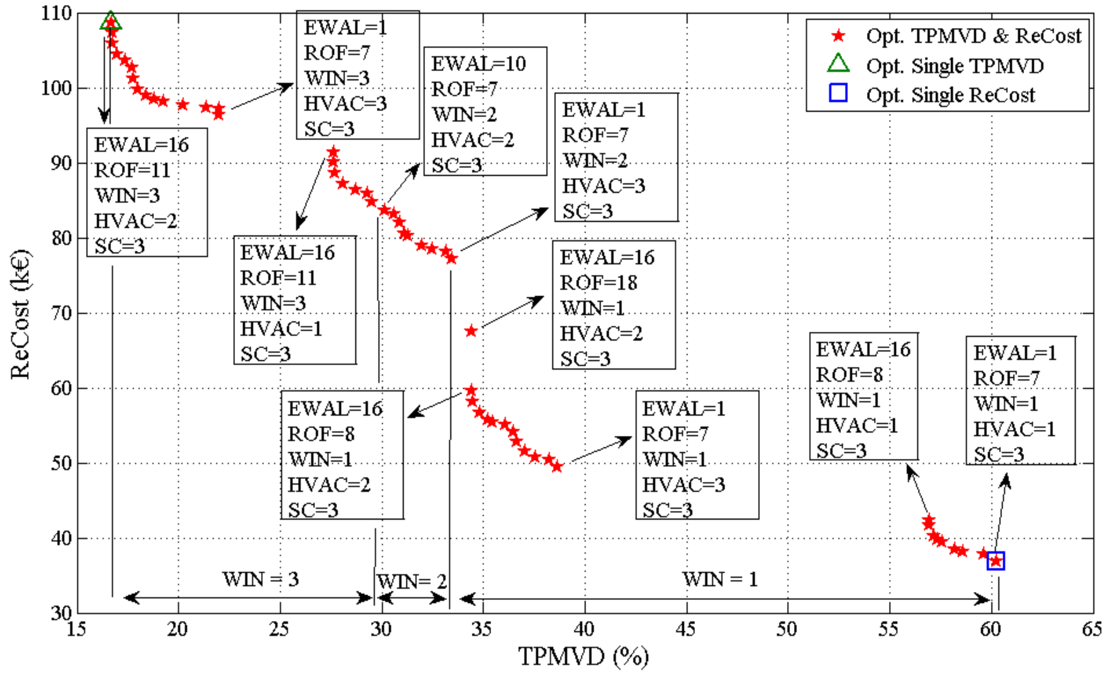

Figure 4-23 Multi-objective solutions for the building retrofit strategies (TPMVD - ReCost) (Refer to Appendix B.3 for RAs characteristics)

The three sets of optimization presented above resulted in the following conclusions:

- The number of non-dominated solutions generated seems to depend on the chosen objectives, and the number of non-dominated solutions for objectives with similar characteristics is lower than for those with dissimilar characteristics.
- The analysis of the results shows the physical characteristics of solutions and helps to understand the simultaneous influence of the decision variables on the EC, ReCost, and TPMVD.

- Without considering a constraint on summer overheating, the influence of the window type on the results is more significant than the influence of the other decision variables.
- There are often discontinuities in the Pareto front where it is possible to gain a lot in one objective sacrificing only a little in the other objective.

4.2.4.3 Third set of optimization (three-objectives)

The three objectives dealt with in this set of optimization were energy consumption, retrofit cost, and total percentage of discomfort hours. They were treated simultaneously, and the optimized solutions formed a Pareto surface in three dimensions. The results are given in 3D in Figure 4-24, and in 2D projections in Figure 4-25 and Figure 4-26. In this visualization, which gives the results for all three objectives, the Pareto surface synthesizes the different solutions.

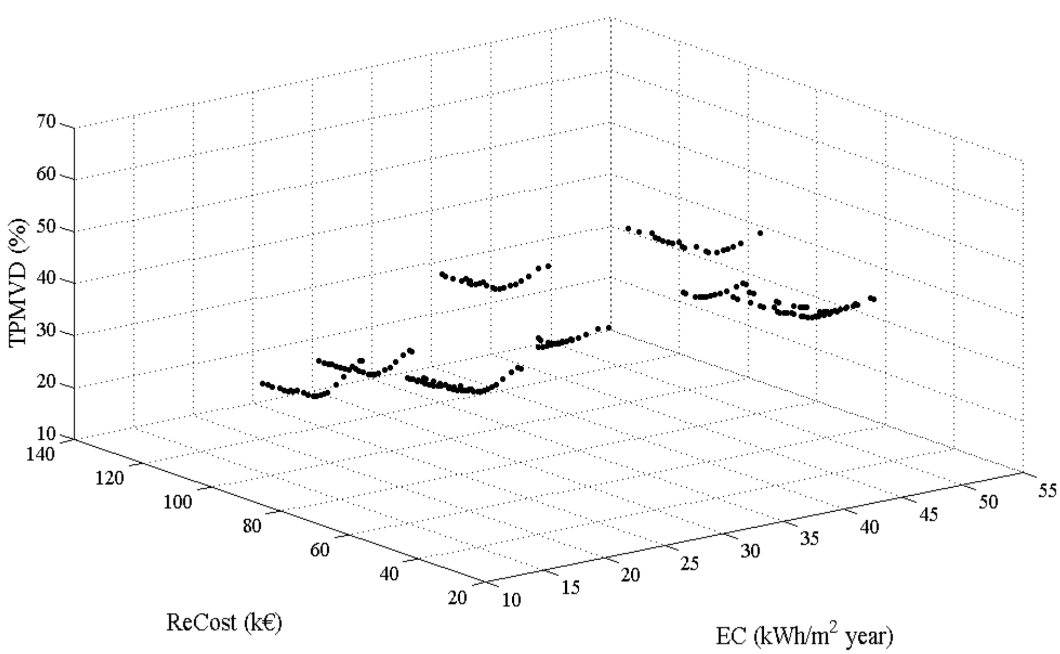

Figure 4-24 Results of multi-objective optimization - 3D visualization

Figure 4-25 illustrates a 2D projection for energy consumption and retrofit cost, including the corresponding TPMVD color map. Figure 4-26 presents a 2D projection for energy consumption and TPMVD, including corresponding ReCost color map. This color map is not a surface and is used as a visual aid to help determining the values of the third objective function (not in the horizontal and vertical axes). It is worthwhile to mention that the obtained non-dominated solutions on the Pareto front are found to be classified according to the window type and HVAC or solar collector type in each set.

From Figure 4-25 and Figure 4-26, it can be seen that, achieving EC values lower than 20 [kWh/m^{2}year] is possible with thick wall and roof insulation material and double glazed window type 3. Besides, an HVAC system with no cooling option should necessarily be selected to obtain the lowest EC values. This set of non-dominated solution lead to TPMVD values not greater than 30%. Except this set of non-dominated solutions, the other solutions with the HVAC type 1 resulted to high thermal discomfort hours (more than 45%).

The HVAC system and window type played a big role in changing the TPMVD values of the set of non-dominated solutions. For example, to attain TPMVD values lower than 20%, the HVAC type 2 or 4, with cooling option and window type 3 with lowest thermal transmittance value are selected to minimize the thermal discomfort hours in the building, as depicted in Figure 4-25.

To obtain non-dominated solutions of minimum ReCost, the HVAC system type 1 with no cooling option, and the window type 1 that is a single glazed window, both with lowest price among the set of HVAC and window retrofit actions, is found to be optimal. However this set of non-dominated solutions resulted in the highest number of thermal discomfort hours in the building. Therefore the optimization led to HVAC option 2 and 3, with the same window, to achieve better thermal comfort in the building (Figure 4-25).

Nevertheless, this set of non-dominated solution resulted in higher energy consumption (EC more than 42 [kWh/m^{2}year]).

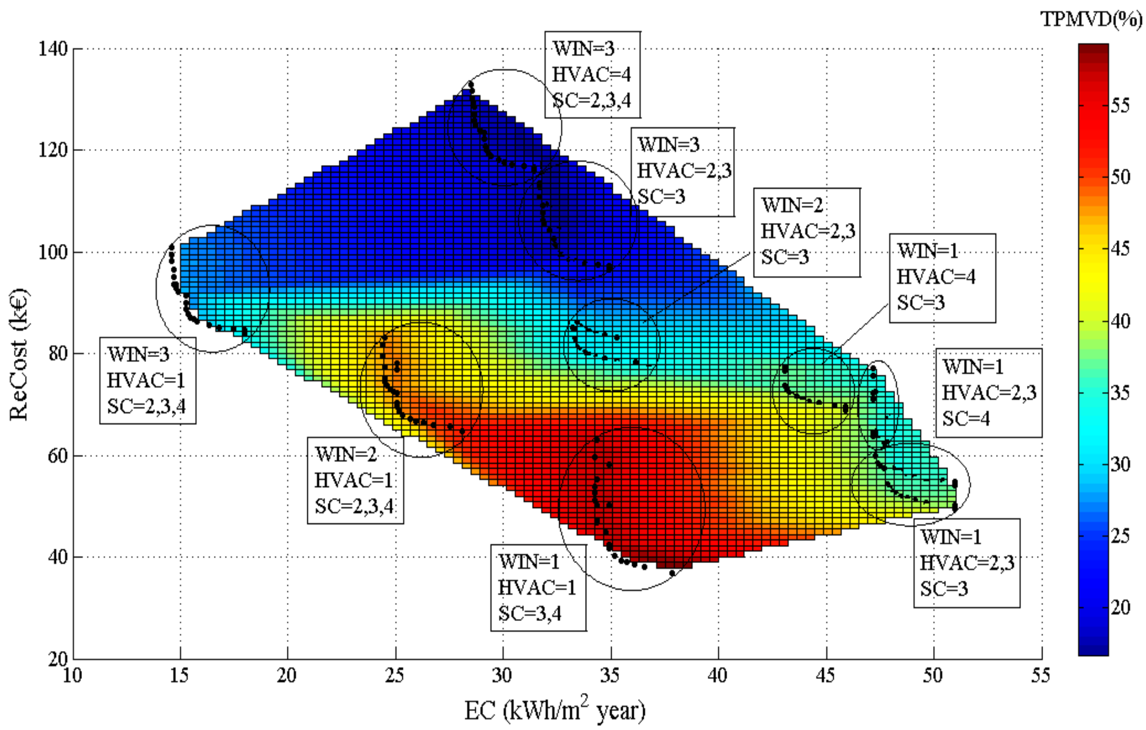

Figure 4-25 Results of multi-objective optimization of EC, ReCost and TPMVD - 2D projection (EC – ReCost) (Refer to Appendix B.3 for RAs characteristics)

Figure 4-26 shows that at the value of EC 28 [kWh/m^{2}year], reaching TPMVD values less than 25% or more than 45% is possible. This can be shown by points (A) and (B). Point (A) has TPMVD of 51.92% which is higher than that for point (B), which is 18.19%. For the latter, a double glazed window with lowest thermal transmittance (WIN = 3) among all the windows considered, and HVAC system type 4 with cooling option were implemented to lower summer overheating and consequently decrease the TPMVD value. To keep the same level of EC, the optimization solver selected HVAC system type 1 without cooling option and window type 2 which has lower cost. This led to sacrificing thermal comfort (TPMVD value reached to 51.92% from 18.19%). However, moving from point (A) to point (B), required an additional investment of 60 k€.

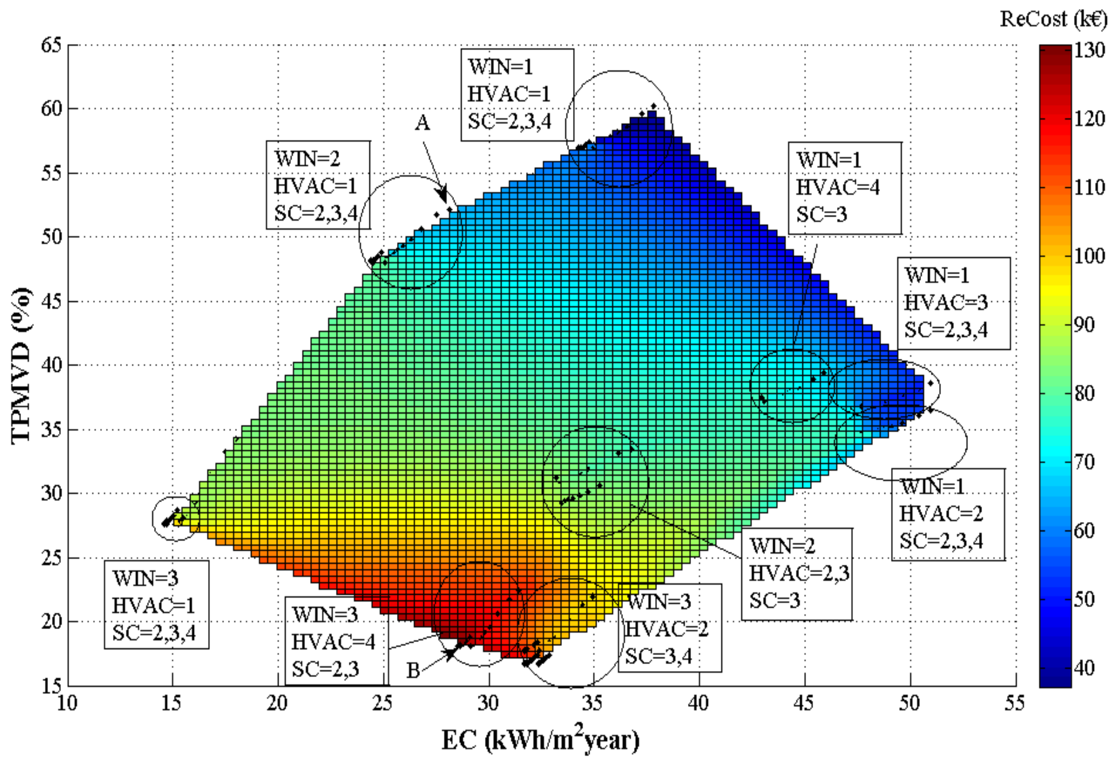

Figure 4-26 Results of multi-objective optimization of EC, ReCost and TPMVD - 2D projection (EC – TPMVD) (Refer to Appendix B.3 for RAs characteristics)

The most important conclusions from the optimization presented above are:

- Regarding the characteristics of the envelope, the simultaneous optimization of three objectives gave a large diversity of retrofit actions.
- The obtained non-dominated solutions found to be classified according to the window type and HVAC or solar collector type in each set. The influence of the window type and HVAC system on the results is more significant than the influence of the other decision variables.

- For achieving the best indoor thermal comfort (lowest TPMVD values), investing in high price HVAC system could be a better solution than investing in additional insulation and other low-energy measures.
- TPMVD values in the range of 20 to 30% are achievable even with a HVAC type without cooling option. In case this range of TPMVD value is acceptable by the DM, the set of non-dominated solution with HVAC system type 1, window type 3 and thick layer of external wall and roof insulation would be the cheapest means to attain low EC and ReCost values. However, were the DM to be slightly more ambitious at the investment stage (retrofit cost), coupling HVAC system type 2 would provide very low TPMVD values.
- The large number of solutions might be considered either as an advantage or a disadvantage: on the one hand, there is a large variety of interesting retrofit actions recommendation; on the other hand, it may be difficult to choose between them.

In sum, these set of optimizations were successfully accomplished. The spreading of the solutions was satisfactory. The selected retrofit actions in the optimal solutions appear to be relevant, and most of them effectively vary along the optimal front.

This set of optimizations highlights the major advantage of a multi-objective formulation, which is to provide a thorough understanding of the trade-offs between the competitive objectives, and bring the potential of each investment into focus.

4.3 CONCLUSION

A multi-objective optimization model based on GAINN approach was applied to a school building case study. Although it required a significant amount of training data, the ANN was able to accurately approximate the existing building simulation software results. Thanks to this ANN, each multi-objective optimization was undertaken with a computational time as low as 9 minutes. The total computational time associated with the whole optimization (i.e. including ANN training and validation) is approximately 3 days. In case an exhaustive-computation search method is implemented, then 24×18×3×4×4=20,736 simulation runs are needed to obtain all possible candidate solutions. The execution time of one simulation run is about 5.19 min. This means that 75 days would be required to get the exhaustive search results for the predefined problem. In other words, this optimization would have never been practical without using the proposed approach.

Regarding the optimization results, the single-objective optimization provided an understanding of the impact of each set of retrofit actions and objective function on the building's overall performance after retrofit. Following that, the proposed multi-objective algorithm produced a wide range of non-dominated solutions. The model assessed their overall performance, while at the same time quantifying the impact of their individual components. Furthermore, 2D and 3D graphical representation of non-dominated frontier unveils the trade-offs between the competitive objectives.

Moreover, using the graphs, one can ascertain the impact on thermal comfort and retrofit cost of any reduction or increase in the energy consumption. The final decision can therefore be based on a real understanding of the situation, and of the impact of energy consumption on thermal comfort and retrofit cost. It is worthwhile to mention that the search space, and therefore the set of non-dominated solutions, depends on the alternative retrofit actions considered and the constraints that may be imposed to allow their combination.

The proposed approach shows a great potential for the solution of multi-objective building retrofit problems, and can be used as an aid to decision-making in the context of a retrofit project. Knowing what can be feasibly achieved and what trade-offs are at stake, the DMs can progress towards the choice of the best compromise solutions by inserting constraints of the levels of the objective functions, for instance, or look for the solution that is closer to their aspiration levels.

CHAPTER 5
CONCLUSION, LIMITATION AND FUTURE WORK

Summary:

What are the main conclusions of this thesis?

What are the main limitations of the proposed models?

What are the future works to complement this study?

Chapter 5: Conclusion, Limitation and Future work

This thesis presents a set of multi-objective optimization models to support the decision process for improving energy efficiency and indoor environmental quality in the course of a building retrofit project. Chapter 2 presents a comprehensive review of the existing approaches towards improvement of energy efficiency in buildings. Chapter 3 is devoted to the development of two models using a Tchebycheff optimization technique to tackle the multi-objective optimization problem of building retrofit. Chapter 4 focuses on the development of an optimization model based on the GAINN approach.

The observations and conclusions of each chapter can be summarized as follows.

5.1 State-of-the-art on existing building retrofit

This chapter aimed at providing an overview of the recent research and development in the field of building retrofit. This review provided an understanding of methodologies used in previous studies and how their limitations could be overcome. Different methodologies for assisting decision making in the appraisal of retrofit actions have been categorized into two main approaches: approaches in which alternatives are explicitly known *a priori* (MCDA approaches) and approaches in which alternatives are implicitly defined in the setting of an optimization model (MOP approaches). Furthermore these approaches were subcategorized and analyzed in detail.

It has been concluded that the main problem when employing MCDA techniques is that they are applied upon a set of predefined alternative courses of action. In case that a limited number of such alternatives have been defined, there is no guarantee that the solution finally reached is the optimal one. Also, the selection of a representative set of alternatives is usually a difficult problem, while the final solution is heavily affected by these predefined alternatives. On the opposite case, when numerous alternatives are defined, the required evaluation and selection process may become extremely difficult to handle. Moreover, the MCDA approaches reviewed did not provide the DMs with information about the trade-offs between the objective functions.

MOP approaches tackle building retrofit problems not requiring to enumerate the set of actions to be considered. Furthermore, the fact that MOP enables the characterization of the non-dominated front and the trade-offs at stake between the objective functions is one of its main advantages. Multi-objective models enable the DMs to grasp the conflicting nature of the objectives and the trade-off to be made in order to identify satisfactory compromise solutions by providing a basis to rationalize the comparison between non-dominated solutions. However, it was then discussed that the concept of non-dominated solution is a poor one, in the sense that it lacks discriminative power for decision recommendation purposes.

5.2 Multi-objective optimization of a residential building using a Tchebycheff optimization technique

Two multi-objective optimization models using a Tchebycheff technique were presented in Chapter 3. The first approach uses a thermal model of the building based on the current methodology of the Portuguese building thermal code (RCCTE) to assess existing building condition and retrofit actions. The second approach benefits from TRNSYS simulation software for energy and comfort assessment. Chapter 3 also presented an example of application of the proposed models in a residential building. These models took into account all considered combinations of choices concerning different insulation materials for roof and wall, windows and solar collectors. The DM was offered solutions corresponding to different trade-offs between energy savings and retrofit costs in the first model, and thermal comfort besides the already mentioned objectives in the second model.

Both models allowed explicitly for the consideration of all available combinations of alternative retrofit actions. The result of the application of the Tchebycheff programming technique showed the feasibility of this methodology to find well balanced strategies for retrofitting of a building, to be presented to a DM in the context of a decision support process.

However, since retrofit action assessment in the thermal-model based approach relies on RCCTE, the model does not allow for consideration of all desired objective functions such as thermal comfort. Besides, this thermal code was developed for residential buildings, so application of the model to other types of building is not adequate.

The simulation-based model solved the above mentioned problems by using TRNSYS as a building simulation and retrofit assessment engine. However, the further consideration of all possibilities that the DM has available for building retrofit, as well as all the objectives that he/she may wish to optimize, led to a combinatorial explosion of the decision space, thus making the solving procedure extremely difficult and time-consuming.

5.3 MULTI-OBJECTIVE OPTIMIZATION OF A RESIDENTIAL BUILDING USING THE GAINN APPROACH

Chapter 4 presented a multi-objective optimization model based on the GAINN approach to assess technology choices in a building retrofit project. The benefits of this approach with respect to the classical optimization models previously presented are its rapidity and computational efficiency.

The proposed methodology was used for the optimization of the energy consumption, retrofit cost and thermal comfort in a school building. According to the validation results, the ANN was able to accurately predict the studied objective functions, although it required a significant amount of training data. Using ANN, the multi-objective optimization was undertaken with a very low computational time.

It can be concluded that the proposed methodology based on the GAINN approach shows great potential for the solution of the multi-objective building retrofit problems, and can be used as an aid to decision-making in the context of a retrofit project.

5.4 FUTURE WORK

The proposed methodology based on the GAINN approach still has several limitations that should be dealt with in order to lead to a robust method to assess technology choices in a building retrofit project. The following limitations of the model should be addressed in future research:

- **Selecting the optimal solution**: It is necessary to combine the proposed model with mechanisms to incorporate the DM's preferences into the decision aid process. The current model reports the identification of the set of non-dominated solutions. It is then necessary to reach a final compromise solution for practical implementation or a reduced set of non-dominated solution for further screening. For this purpose, the proposed multi-objective optimization methodology should be combined with MCDA approaches for the selection of the best compromise solution(s).
- **ANN training and validation**: In the case study, the rule of thumb stating that using LHS a number of cases greater than twice the number of parameters is sufficient for ANN training did not apply. The additional need for training data multiplies the computational time and therefore it should be taken into account in future work. While the approach remains valuable in terms of time saving, further

studies should be performed regarding the number of cases to be used for ANN training in order to make sure that the ANN would be accurate in all situations. The opportunity of using other sampling methods rather than LHS and other training methods should be studied. The ANN construction and specially the number of neurons in the hidden layer is not obvious either. The number of hidden neurons and number of cases for training should be more carefully studied for building applications, and guidelines should be proposed.

- **Accounting for different climatic zones**: The current neural network model has been developed for the ESQF school building that is located in Coimbra. This model must be trained with different weather files to account for the climatic zones in Portugal in order to assess similar school buildings.
- **Performing uncertainty assessment**: A building retrofit is subject to many uncertainty factors, such as in savings estimation, energy use measurements, weather forecast, retrofit actions cost data, etc. These factors result that investment in building retrofit is highly uncertain. Uncertainty assessment is therefore essential to provide the DMs with a sufficient level of confidence to select and determine the best retrofit solutions. While there are many uncertainty assessment and uncertainty management methods available, probability-based risk assessment methods are probably the most commonly used methods. Probability-based risk assessment methods include expected value analysis, mean-variance criterion and coefficient of variation, risk adjusted discount rate technique, certainty equivalent technique, Monte Carlo simulation, decision analysis, real options and sensitivity analysis.
- **Application of the proposed model for on-line optimization**: A promising application of the proposed methodology based on GAINN would be to use it for

on-line systems. This enables to obtain the best combination of retrofit actions in a very short time in the course of a retrofit project. One of the main problems of building retrofit is the computational time dealing with building simulation and energy assessment. The proposed methodology could overcome this drawback by using the ANN to provide fast predictions of building behavior, and then find the best set of retrofit actions in the context of a retrofit project. The need for training the data for the ANN would not be an issue in this case, since on-line optimization generally involves continuous monitoring of the building. Data could therefore be continuously stored, so the ANN training could become more efficient each day, making the proposed methodology more accurate.

Appendices

APPENDIX A NOMENCLATURE

Table A.1 Nomenclature (Abbreviations)

Symbol	Designation	Unit
ANN	Artificial Neural Network	-
BREEAM	BRE Environmental Assessment Method	-
CASBEE	Comprehensive Assessment for Built Environment Efficiency	-
CEN	Centre Européen de Normalisation	-
CFD	Computational Fluids Dynamics	-
CMAA	Construction Management Association of America	-
DHW	Domestic Hot Water	-
DM	Decision Maker	-
ECM	Energy Conservation Measure	-
EPBD	Energy Performance of Buildings Directive	-
ESQF	The Quinta das Flores secondary school	-
EU	European Union	-
EWAL	External Wall insulation material	-
GA	Genetic Algorithm	-
GAINN	Genetic Algorithm Integrating Neural Network	-
HKBEAM	Green Building Design and Building Environmental Assessment	-
HVAC	Heating, Ventilation, and Air-Conditioning	-
IAQ	Indoor Air Quality	-
IEQ	Indoor Environmental Quality	-
IRR	Internal Rate of Return	-
ISO	International Organization for Standardization	-

LCC	Life Cycle Cost	-
LEED	Leadership in Energy and Environmental Design	-
LHS	Latin Hypercube Sampling	-
M & V	Measurement and Verification	-
MAUT	Multiple Attribute Utility Theory	-
MCDA	Multi-Criteria Decision Analysis	-
MOGA	Multi-Objective Genetic Algorithm	-
MOO	Multi-Objective Optimization	-
MOP	Multi-Objective Programming	-
NN	Neural Network	-
NPV	Net Present Value	-
NSGA	Non-dominated Sorting Genetic Algorithm	-
PMV	Predicted Mean Vote	-
PPD	Percentage of People Dissatisfied	-
PV	Photovoltaic	-
RA	Retrofit Action	-
RCCTE	Portuguese residential building thermal code	-
RMSE	root mean square errors	-
ROF	Roof insulation material	-
SC	Solar Collector	-
SHW	Sanitary Hot Water	-
TRNSYS	Transient Energy System Simulation Tool	-
WIN	Window	-

Table A.2 Nomenclature

Symbol	Designation	Unit
x_i^{EWAL}	Wall insulation material type i	-
x_j^{ROF}	Roof insulation material type j	-
x_k^{WIN}	Window type k	-
x_l^{SC}	Solar Collector type l	-
x^{EWAL}	External wall insulation material type identifier	-
x^{ROF}	Roof insulation material type identifier	-
x^{WIN}	Window type identifier	-
x^{SC}	Solar collector type identifier	-
x^{HVAC}	HVAC system type identifier	-
E_{pre}	energy use predicted from a pre-retrofit model of the facility	[kWh/year]
E_{post}	energy used in the facility after implementing the retrofit actions	[kWh/year]
ES	Energy Savings	[kWh/year]
Q_{ic}	Annual energy need for space heating	[kWh/year]
Q_{vc}	Annual energy need for space cooling	[kWh/year]
Q_{ac}	Annual energy need for domestic hot water	[kWh/year]
X_o	Orientation coefficient for the different façade orientations	-
$Q_t(x)$	Total heat loss by the building envelope	[kWh/year]
Q_v	Total heat loss by air renovation	[kWh/year]
$Q_{gu}(x)$	Total heat gains (internal + solar heat gains through glazing)	[kWh/year]
$Q_{ext}(x)$	Total heat loss through zones in contact with outdoor (walls, glazing, roofs and pavements)	[kWh/year]
Q_{enu}	Total heat loss through zones in contact with non-heated spaces (walls, glazing, roofs and pavements)	[kWh/year]
Q_{pt}	Total heat loss through linear thermal bridges	[kWh/year]

DD_H	Heating degree-days	[ºC.day]
$BLC_{ext}(x)$	Building load coefficient	[W/ ºC]
A_{EWAL}	Exterior wall surface area	[m^2]
d_i	Thickness of the external wall insulation type i	[m]
A_{ROF}	Roof surface area	[m^2]
d_j	Thickness of the roof insulation type j	[m]
A_{WIN}	Windows surface area	[m^2]
U_k	Window type k thermal transmission coefficient	[W/m^2.ºC]
A_{enu}	Area of building envelope elements in contact with non-heated spaces	[m^2]
U_{enu}	Thermal transmission coefficient of elements in contact with non-heated spaces	[W/m^2.ºC]
B	Floor or wall interior linear perimeter for envelope in contact with the soil or interior length of thermal bridge	[m]
ACH	Air changes per hour	[h^{-1}]
Ap	Net floor area	[m^2]
P_d	Floor to ceiling height	[m]
M	Heating season duration	[Months]
q_i	Internal heat gains	[W/m^2]
G_{south}	Average monthly solar energy that reaches a south oriented vertical surface	[kWh/m^2.month]
A_e	Effective glazing area for the different windows orientations	[m^2]
F_S	Shading factor	-
F_g	Glazing factor	-
F_W	Correction factor for movable shading devices for cooling calculation	-
$g_{\perp ver}$	Effective total solar energy transmittance of glazing	-
Ir	Total average solar radiation intensity for each orientation	[kwh/m^2]
h_e	Thermal conductivity of external building envelope, that is equal to 25	[W/m^2.ºC]

Q_1	Total heat gains through building envelope	[kwh/year]
Q_2	Total heat transfer due to air infiltration	[kwh/year]
Q_3	Total internal heat gains	[kwh/year]
Q_4	Total heat gains through glazing	[kwh/year]
M_{AQS}	Average daily consumption of DHW	[L/day]
nd	Total number of days with DHW consumption	-
$E_l^{sol}(x)$	Total energy contribution from solar collector type l	[kWh/year]
E_{ren}	Total energy contribution from other renewable sources	[kWh/year]
Q_{ac}	Annual DHW heating needs	[kWh/year]
Q_a	Total energy supplied with conventional systems for DHW	[kWh/year]
E_{heat}	annual energy demand for space heating [kWh/year]	[kWh/year]
E_{cool}	annual energy demand for space cooling	[kWh/year]
E_{DHW}	annual energy demand for DHW	[kWh/year]
$E_{heat,i}^{EWAL}$	total energy demand for space heating after implementation of external wall insulation material type *i*	[kWh/year]
$E_{heat,j}^{ROF}$	total energy demand for space heating after implementation of roof insulation material type *j*	[kWh/year]
$E_{heat,k}^{WIN}$	total energy demand for space heating after implementation of window type *k*	[kWh/year]
$E_{cool,i}^{EWAL}$	total energy demand for space cooling after implementation of external wall insulation material type *i*	[kWh/year]
$E_{cool,j}^{ROF}$	total energy demand for space cooling after implementation of roof insulation material type *j*	[kWh/year]
$E_{cool,k}^{WIN}$	total energy demand for space cooling after implementation of window type *k*	[kWh/year]
$E_{DHW,l}^{SC}$	total energy demand for domestic hot water system after implementation of solar collector type *l*	[kWh/year]
TPMVD	total percentage of discomfort hours	%

k	Conductivity	[kJ/hr.m.K]
p	Tchebycheff programming weighting vector	-
R	Resistance	[m^2K/W]
EC	Energy Consumption	[kWh/m^2year]
QHEAT	energy consumption for space heating	[kWh/m^2year]
QCOOL	energy consumption for space cooling	[kWh/m^2year]
QSC	Heating production by Solar Collector	[kWh/m^2year]
QSHW	Energy consumption for sanitary hot water	[kWh/m^2year]
E_p	Primary Energy	[kWh/year]
C^{HVAC}	cost for selected HVAC system	[€]
C_i^{EWAL}	cost in [€/m^2] for external wall insulation material type i	[€/m^2]
C_j^{ROF}	cost in [€/m^2] for roof insulation material type j	[€/m^2]
C_k^{WIN}	cost in [€/m^2] for window type k	[€/m^2]
C_l^{SC}	cost for solar collector type l	[€]
ReCost	Retrofit Cost	[€]

Table A.3 Nomenclature (Greek Symbols)

Symbol	Designation	Unit
ΔT	Difference of temperature to heat the water	[˚C]
α	Exterior envelope solar radiation absorption coefficient	-
θ_m	Average outdoor temperature in the cooling season	[˚C]
η_{arref}	Heat gain utilization factor for cooling season	-
η_a	DHW system efficiency	-
r	Density	[kg/m^3]
C_p	Specific Heat	[kJ/kg.K]
τ	Losses to non-heated spaces reduction coefficient	[kWh/year]
Ψ	Linear heat flux transmission coefficient	[W/m.ºC]
λ_i	Thermal conductivity of the external wall insulation material type i	[W/m.ºC]
λ_j	Thermal conductivity of the roof insulation material type j	[W/m.ºC]
η_{aq}	Heat gains utilization factor for heating season	-
θ_{iH}	Internal heating set point	℃
θ_{iC}	Internal cooling set point	℃

APPENDIX B RETROFIT ACTIONS CHARACTERISTICS

This Appendix presents the tables regarding to different considered retrofit actions in Chapters 3 and 4. The different associated retrofit action costs are derived from the CYPE rehabilitation price generator, which is a tool that enables users to get prices with cost estimates adjusted to reality as much as possible.

B.1 List of retrofit actions in Chapter 3-1

In this section alternative retrofit actions considered in Chapter 3-1 are presented. Alternative RAs related to different external wall and roof insulation materials are displayed in Tables B.1 and B.2. Different alternative choices regarding windows are displayed in Table B.3. Finally different solutions for solar collectors are presented in Table B.4.

Table B.1 Characteristics of alternative external wall insulation materials

No.	Insulation types	Thickness (m)	Thermal conductivity (W/m ^{0}C)	Cost (€/m^2)
1	MW (mineral wool)	0.03	0.034	11.25
2		0.04	0.034	13.21
3		0.05	0.034	15.51
4		0.06	0.034	17.65
5		0.08	0.034	21.95
6		0.04	0.037	14.05
7		0.03	0.035	10.5
8		0.04	0.035	12.4
9		0.05	0.035	14.27
10		0.05	0.034	15.53

11		0.06	0.034	17.73
12		0.03	0.034	11.45
13		0.04	0.034	13.47
14		0.05	0.034	15.84
15		0.06	0.034	18.04
16		0.08	0.034	22.48
17	Glass Wool	0.05	0.038	12.67
18		0.04	0.036	10.99
19		0.05	0.036	12.29
20		0.06	0.036	12.95
21		0.08	0.036	15.45
22	EPS (expanded polystyrene)	0.03	0.036	7.64
23		0.04	0.036	8.34
24		0.05	0.036	9.03
25		0.06	0.036	9.74
25		0.07	0.036	10.44
27		0.08	0.036	11.15
28		0.03	0.033	9.59
29		0.04	0.033	10.96
30		0.05	0.033	12.31
31		0.06	0.033	13.66
32		0.07	0.033	15.03
33		0.08	0.033	16.38
34		0.03	0.036	7.39
35		0.04	0.036	8.1

36		0.05	0.036	8.83
37		0.06	0.036	9.56
38		0.03	0.033	8.64
39		0.04	0.033	9.75
40		0.05	0.033	10.68
41		0.06	0.033	11.99
42	Sprayed Polyurethane	0.02	0.042	6.39
43		0.03	0.042	8.34
44		0.04	0.042	10.98
45		0.05	0.042	13.4
46	Cork	0.01	0.04	3.05
47		0.02	0.04	3.95
48		0.03	0.04	5.55
49		0.04	0.04	7.18
50		0.05	0.04	8.98
51		0.06	0.04	10.77
52		0.08	0.04	14.36
53		0.10	0.04	17.95
54		0.15	0.04	26.93
55		0.20	0.04	35.90
56		0.30	0.04	53.85

Table B.2 Characteristics of alternative roof insulation materials

No.	Insulation types	Thickness (m)	Thermal conductivity (W/m ^{0}C)	Cost (€/m^2)
1	Sprayed Polyurethane	0.02	0.042	6.39
2		0.03	0.042	8.34
3		0.04	0.042	10.98
4		0.05	0.042	13.4
5	EPS (expanded polystyrene)	0.03	0.033	4.32
6		0.04	0.033	5.6
7		0.05	0.033	6.87
8		0.06	0.033	8.14
9		0.07	0.033	9.43
10		0.08	0.033	10.7
11	XPS (extruded polystyrene)	0.04	0.034	11.64
12		0.05	0.034	14.43
13		0.06	0.034	17.22
14		0.08	0.034	22.78
15	Stone wool	0.065	0.037	24.67
16		0.085	0.037	31.3
17		0.105	0.037	34.8

Table B.3 Characteristics of alternative windows

No.	Type	Thermal transmittance ($W/m^2\ {}^0C$)	Effective solar energy transmittance (%)	Cost (€/m^2)
1	Single glazing Typical glazing	5.10	85.00	34.08
2	2bl glazing Without thermal break Uncoated air -filled metallic frame 4-12-4	2.80	75.00	39.42
3	2bl glazing Without thermal break Uncoated air -filled metallic frame 6-12-4	2.80	72.00	46.24
4	2bl glazing Without thermal break Uncoated air -filled metallic frame 6-12-6	2.80	72.00	53.06
5	2bl glazing Without thermal break Uncoated air -filled metallic frame 8-12-4	2.80	69.00	56.78
6	2bl glazing Without thermal break Uncoated air -filled metallic frame 8-12-6	2.80	69.00	63.59
7	2bl glazing Without thermal break Uncoated air -filled metallic frame 8-12-8	2.70	67.00	74.13
8	2bl glazing Without thermal break Uncoated air -filled metallic frame 4-16-4	2.70	75.00	40.31
9	2bl glazing Without thermal break Uncoated air -filled metallic frame 6-16-4	2.70	72.00	47.14
10	2bl glazing Without thermal break Uncoated air -filled metallic frame 6-16-6	2.60	72.00	53.96
11	2bl glazing Without thermal break Uncoated air -filled metallic frame 8-16-4	2.60	69.00	57.68

12	2bl glazing Without thermal break Uncoated air -filled metallic frame 8-16-6	2.60	69.00	64.50
13	2bl glazing Without thermal break Uncoated air -filled metallic frame 8-16-8	2.60	67.00	75.04
14	2bl glazing Low-e window (with thermal break) coated air-filled metallic frame 4-12-4 ISOLAR Glass	2.80	75.00	46.92
15	2bl glazing Low-e window (with thermal break) coated air-filled metallic frame 4-12-4 NEUTRALUX	1.60	62.00	55.72
16	2bl glazing Low-e window (with thermal break) coated air-filled metallic frame 4-12-4 NEUTRLALUX*-S	1.60	53.00	57.93
17	2bl glazing window air-filled metallic frame 6-12-4 SOLARLUX Neutro 62 Temprado	2.10	50.00	118.60
18	2bl glazing window air-filled metallic frame 6-12-4 SOLARLUX Natural 60/40 Temprado	1.60	42.00	143.42
19	2bl glazing window air-filled metallic frame 6-12-4 SOLARLUX Supernatural 68 Temprado	1.60	38.00	180.77
20	2bl glazing window air-filled metallic frame 6-12-4 SOLARLUX Supernatural 52/25 Temprado	1.60	28.00	192.20
21	2bl glazing window air-filled metallic frame 6-12-4 SOLARLUX Supernatural 70/40 Temprado	1.60	44.00	135.53

Table B.4 Characteristics of alternative solar collector systems

No.	Type	E_Solar (kWh)	Cost (€/m^2)
1	AZIMUT115P1 (1plain collector with Thermosyphon)	724	1551.61
2	AZIMUT145P1 (1plain collector with Thermosyphon)	1061	1645.1
3	AZIMUT192P2 (2plain collector with Thermosyphon)	1865	2402.27
4	JUNKERS (1plain collector with Thermosyphon) A1/TS150/FKB	1048	1900.9
5	JUNKERS (2plain collector with Thermosyphon) A1/TS150/FKB	1900	3135.54
6	DANOSA SOLAR TDS150/CIS (1plain collector with Thermosyphon)	1048	1465.47
7	DANOSA SOLAR TDS200/CIS (2plain collector with Thermosyphon)	1900	2113.5
8	JUNKERS (2plain collector with Thermosyphon) A1/TS150/FKB Inclination39	1920	3135.54
9	AZIMUT192P2 (2plain collector with Thermosyphon) Inclination35	1882	2402.27

Note - E_Solar(kWh) that is the energy production from solar collector has been calculated by SOLTERM software that is developed by the Portuguese National Laboratory for Energy and Geology (LNEG).

B.2 List of retrofit actions in Chapter 3-2

In this section alternative retrofit actions considered in Chapter 3-2 are presented.

Table B.5 Characteristics of alternative external wall insulation materials

N	Insulation types	Name	t Thickness (m)	U-value (W/m^2K)	c Cost (€/m^2)
1	Cork	OUTWALL_CORKHIGH3	0.03	1.408	5.55
2		OUTWALL_CORKHIGH4	0.04	1.124	7.18
3		OUTWALL_CORKHIGH5	0.05	0.935	8.98
4		OUTWALL_CORKHIGH6	0.06	0.800	10.77
5		OUTWALL_CORKHIGH7	0.07	0.699	12.23
6		OUTWALL_CORKHIGH8	0.08	0.621	14.36
7		OUTWALL_CORKHIGH9	0.09	0.559	16.78
8		OUTWALL_CORKHIGH10	0.1	0.508	17.95
9	EPS	OUTWALL_EPSLOW3	0.03	0.800	7.64
10		OUTWALL_EPSLOW4	0.04	0.621	8.34
11		OUTWALL_EPSLOW5	0.05	0.508	9.03
12		OUTWALL_EPSLOW6	0.06	0.429	9.74
13		OUTWALL_EPSLOW7	0.07	0.372	10.44
14		OUTWALL_EPSLOW8	0.08	0.328	11.15
15		OUTWALL_EPSLOW9	0.09	0.293	12.35
16		OUTWALL_EPSLOW10	0.1	0.265	13.68
17	XPS	OUTWALL_XPSLOW3	0.03	0.800	9.65
18		OUTWALL_XPSLOW4	0.04	0.621	11.64
19		OUTWALL_XPSLOW5	0.05	0.508	14.43
20		OUTWALL_XPSLOW6	0.06	0.429	17.22
21		OUTWALL_XPSLOW7	0.07	0.372	19.34
22		OUTWALL_XPSLOW8	0.08	0.328	22.78
23		OUTWALL_XPSLOW9	0.09	0.293	24.43
24		OUTWALL_XPSLOW10	0.1	0.265	26.78

Table B.10 Characteristics of alternative roof insulation materials

N	Insulation types	Name	t Thickness (m)	U-value (W/m^2K)	c Cost (€/m^2)
1	XPS (extruded	ROOF_XPS3	0.03	0.800	9.65
2	polystyrene	ROOF_XPS4	0.04	0.621	11.64
3	stone wool)	ROOF_XPS5	0.05	0.508	14.43
4		ROOF_XPS6	0.06	0.429	17.22
5		ROOF_XPS7	0.07	0.372	19.34
6		ROOF_XPS8	0.08	0.328	22.78
7	EPS (expanded	ROOF_EPS3	0.03	0.800	4.32
8	polystyrene)	ROOF_EPS4	0.04	0.621	5.60
9		ROOF_EPS5	0.05	0.508	6.87
10		ROOF_EPS6	0.06	0.429	8.14
11		ROOF_EPS7	0.07	0.372	9.43
12		ROOF_EPS8	0.08	0.328	10.70
13	Polyurethane	ROOF_PU3	0.03	0.658	8.34
14		ROOF_PU4	0.04	0.508	10.98
15		ROOF_PU5	0.05	0.413	13.40
16		ROOF_PU6	0.06	0.348	15.30
17		ROOF_PU7	0.07	0.301	17.86
18		ROOF_PU8	0.08	0.265	20.18

Table B.11 Characteristics of alternative windows

N	Name	Thermal transmittance ($W/m^{2\circ}C$)	Effective solar energy transmittance (%)	Cost (€/m^2)
1	SGSILVER	1.05	28.80	58.70
2	SGPLANISOLGREEN	1.16	26.50	67.82
3	SGCLIMATOP	0.52	58.50	102.25

Table B.12 Characteristics of alternative solar collector systems

N	Type	Name	Generation efficiency (%)	Collector area (m^2)	Cost(€/m^2)
1	Flat collector	FC702	70	2	700
2		FC802	80	2	800
3		FC704	70	4	1250
4		FC804	80	4	1600

B.3 List of retrofit actions in Chapter 4

In this section alternative retrofit actions considered in Chapter 4 are presented. Alternative RAs related to different external wall and roof insulation materials are displayed in Tables B.9 and B.10. Different alternative choices regarding windows are displayed in Table B.11. Finally different solutions for solar collectors and HVAC systems are presented in Tables B.12 and B.13.

Table B.13 Characteristics of alternative external wall insulation materials

No.	Insulation type	Name	t Thickness (m)	U-value (W/m^2K)	c Cost (€/m^2)
1	Cork	OUTWALL_CORKHIGH3	0.03	1.408	5.55
2		OUTWALL_CORKHIGH4	0.04	1.124	7.18
3		OUTWALL_CORKHIGH5	0.05	0.935	8.98
4		OUTWALL_CORKHIGH6	0.06	0.8	10.77
5		OUTWALL_CORKHIGH7	0.07	0.699	12.23
6		OUTWALL_CORKHIGH8	0.08	0.621	14.36
7		OUTWALL_CORKHIGH9	0.09	0.559	16.78
8		OUTWALL_CORKHIGH10	0.1	0.508	17.95
9	EPS	OUTWALL_EPSLOW3	0.03	0.8	7.64
10		OUTWALL_EPSLOW4	0.04	0.621	8.34
11		OUTWALL_EPSLOW5	0.05	0.508	9.03
12		OUTWALL_EPSLOW6	0.06	0.429	9.74
13		OUTWALL_EPSLOW7	0.07	0.372	10.44
14		OUTWALL_EPSLOW8	0.08	0.328	11.15
15		OUTWALL_EPSLOW9	0.09	0.293	12.35

16		OUTWALL_EPSLOW10	0.1	0.265	13.68
17	XPS	OUTWALL_XPSLOW3	0.03	0.8	9.65
18		OUTWALL_XPSLOW4	0.04	0.621	11.64
19		OUTWALL_XPSLOW5	0.05	0.508	14.43
20		OUTWALL_XPSLOW6	0.06	0.429	17.22
21		OUTWALL_XPSLOW7	0.07	0.372	19.34
22		OUTWALL_XPSLOW8	0.08	0.328	22.78
23		OUTWALL_XPSLOW9	0.09	0.293	24.43
24		OUTWALL_XPSLOW10	0.1	0.265	26.78

Table B.14 Characteristics of alternative roof insulation materials

No.	Insulation types	Name	t Thickness (m)	U-value (W/m^2K)	c Cost (€/m^2)
1	XPS (extruded polystyrene stone wool)	ROOF_XPS3	0.03	0.8	9.65
2		ROOF_XPS4	0.04	0.621	11.64
3		ROOF_XPS5	0.05	0.508	14.43
4		ROOF_XPS6	0.06	0.429	17.22
5		ROOF_XPS7	0.07	0.372	19.34
6		ROOF_XPS8	0.08	0.328	22.78
7	EPS (expanded polystyrene)	ROOF_EPS3	0.03	0.8	4.32
8		ROOF_EPS4	0.04	0.621	5.6
9		ROOF_EPS5	0.05	0.508	6.87
10		ROOF_EPS6	0.06	0.429	8.14
11		ROOF_EPS7	0.07	0.372	9.43
12		ROOF_EPS8	0.08	0.328	10.7
13	Polyurethane	ROOF_PU3	0.03	0.658	8.34
14		ROOF_PU4	0.04	0.508	10.98
15		ROOF_PU5	0.05	0.413	13.4
16		ROOF_PU6	0.06	0.348	15.3
17		ROOF_PU7	0.07	0.301	17.86
18		ROOF_PU8	0.08	0.265	20.18

Table B.15 Characteristics of alternative windows

No.	Name	Thermal transmittance (W/m^2°C)	Effective solar energy transmittance (%)	Cost (€/m^2)	Total cost (€)
1	Single glazing Typical glazing	5.16	68.20	34.08	4,785
2	2bl glazing Luxguard SunGuard clear Argon 6/16/4	2.54	58.90	100.05	14,047
3	2bl glazing window Argon-filled 4/16/4	1.4	44.00	145.53	20,432

Table B.16 Characteristics of alternative HVAC systems

N	Type	Name	Brand	Generation efficiency (%) or COP(summer/Winter)	Cost(€)
1	Heating System only	Oil-based Boiler	CR Remeha P320/4 90KW	88	6911.52
2	Heating and Cooling systems	Natural Gas boiler (16368.37€) + Chiller(7821.47€)	CR Remeha P320/4 90KW + York YCSA-80TP 80kW	88/3	24189.84
3		Air Source Heat Pump(6506.05€)	MITSUISHI FDC250 VS/25 kW (3 units)	2.5/3	19518.15
4		Ground Source Heat Pump	Kensa Compact Plantroom 80kW	4.6/15	39000

Table B.17 Characteristics of alternative solar collector systems

N	Type	Name	Brand	Module #	Collector area (m^2)	Cost(€/m^2)	Total Cost(€)
1	Flat collector	FSD10	Saunier Duval	10	20.1	643	12918
2		FSD15	Saunier Duval	15	30.1	643	19377
3	CPC (Compound Parabolic Concentrating) Collector	AS10	Ao Sol	10	19.9	500	9950
4		AS15	Ao Sol	15	29.85	500	14925

Appendix C Paper published at Building and Environment journal: Indoor air quality implementation in a hotel building in Portugal

APPENDIX C PAPER PUBLISHED AT BUILDING AND ENVIRONMENT JOURNAL: INDOOR AIR QUALITY IMPLEMENTATION IN A HOTEL BUILDING IN PORTUGAL

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Indoor air quality audit implementation in a hotel building in Portugal

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A B S T R A C T

Hotels are designed to provide high levels of comfort for guests; however, frequent complaints related to uncomfortable thermal environment and inadequate indoor air quality (IAQ) appear. On the other hand, there is little research concerning IAQ audits of hotels up to now.

This study is aimed to establish and demonstrate the comprehensive IAQ audit approach for hotel buildings, based on Portugal national laws. A 4-star hotel building in Portugal is used as a case study to demonstrate the IAQ audit application and evaluate its comprehensiveness and usefulness to the hotel or facility managers. The systematic approach involves the measurement of physical parameters – temperature (dry bulb), relative humidity and the concentration of the suspended particulate matter (PM_{10}) – the monitoring of the concentrations of selected chemical indicators – carbon dioxide (CO_2), carbon monoxide (CO), formaldehyde (HCHO) and total volatile organic compounds (TVOCs) – and the measurements of biological indicators (bacteria, fungi, *Legionella*). In the present case, air exchange rates are measured by the concentration-decay method using metabolic CO_2 as the tracer gas.

The comprehensive IAQ audit revealed four main problems in the hotel building: (1) insufficient ventilation rate; (2) too high particle concentration in some rooms; (3) contamination by *Legionella* of the sanitary hot-water circuit; (4) poor filtration effectiveness in all air handling units (AHUs).

1. Introduction

Hotels are designed to provide high overall comfort and multifaceted services to guests frequently accustomed to, and willing to pay for exclusive amenities, treatment, and entertainment. Comfortable indoor environment, safety, and reliability are some of the amenities valued by guests. However, little research has been published about the indoor air quality (IAQ) of hotel buildings up to now and most hotel managers often ignore these important issues [1,2]. On the other hand, state-of-the-art technical infrastructure is typically utilized in hotels to provide high levels of comfort, especially thermal comfort. Nevertheless, using energy-intensive space-conditioning systems does not warrant absolute guest's satisfaction [1,3]. Guests frequently complain about thermal discomfort, even where expensive and sophisticated systems are operated. Complaints in hotels are most commonly related to uncomfortable air temperatures (too high or too low), and to the difficulty or impossibility of individual adjustment [3]. Moreover, space conditioning (heating, cooling, and ventilation for the purpose of maintaining high standards of air quality and thermal comfort) typically accounts for about half the total energy consumed in hotels [4,5]. Hence, most hotel designers and managers always pay attention only to the energy consumption of hotels operation. Managers take the management of resources as a major role that inevitably leads to housekeeping's greater emphasis on those tasks with visual satisfaction. Nevertheless, hotels are public places accommodating a vast variety of international travellers; therefore the demand for good IAQ may be higher than for other types of buildings [6].

Teeters et al. [6] claimed that facility managers in the hospitality sector have only reacted to those IAQ problems that have caused immediate irritation to guests or employees. However, inadequate air quality as well as the lack of air circulation is another frequent complaint. In addition, the IAQ of hotel buildings affects the health of guests especially in terms of bacterial contamination. For example, Legionnaire's disease broke out in one USA hotel (182 people illness and 29 deaths in 1976) and more than 60 outbreaks worldwide in hotels, hospitals and offices were reported [7–9]. Furthermore, the severe acute respiratory syndrome (SARS) broke out in "M" hotel in Hong Kong has increased the public awareness to indoor air quality of hotels [8].

On the other hand, the European Parliament and Council approved in December 2002 a directive on the energy performance of buildings 2002/91/EC (EPBD) [10], which introduced the obligation of energy certification of buildings. European Standardization Organization (CEN) has drafted several standards to help the member countries implementing the directive. One of these is the "Indoor environmental input parameters for design and assessment

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of energy performance of buildings", addressing IAQ, thermal environment, lighting and acoustics [11]. The standard specifies design values for indoor environment, values to be used in energy calculations, and methods to verify the specified indoor environment in the buildings [12]. However it does not establish a methodology for IAQ audits of buildings. Portugal, as one of the European Union member states, approved a series of national laws to implement the EPBD [13–15], stating simultaneously that IAQ monitoring of the existing non residential buildings is mandatory, under the rules of RSECE [14]. However, it is not the case for most of the member countries.

In this scope, a comprehensive IAQ audit methodology along with energy audit of buildings should be established in order to identify the indoor air problems. Although, some IAQ monitoring methods have been developed in different countries, most of them are applied to office and hospital buildings [e.g. Ref. [16]]. However, the IAQ monitoring approach that is suitable for the hotel building has not yet been developed [1].

Hence, the purpose of this study is to develop and demonstrate a comprehensive IAQ audit methodology for hotel buildings. The data collected from this approach can be used to assess the air quality in hotel buildings and to identify the indoor air problems. Consequently, the IAQ audit approach proposed here may be helpful for the hotel managers to reduce the health risk from hotel buildings and increase the comfort for guests. Furthermore, the result from IAQ audit shows the necessity of having IAQ audit along with energy audit of buildings. In fact, if just energy parameters are considered, as in the last decades, people's comfort and health can be significantly sacrificed.

2. Indoor air quality audit

2.1. IAQ audit methodology

The proposed IAQ audit follows a systematic approach with portable equipment, involving the measurement of physical parameters (temperature (dry bulb), relative humidity and the concentration of the suspended particulate matter (PM_{10})), the monitoring of the concentrations of selected chemical indicators (carbon dioxide (CO_2), carbon monoxide (CO), formaldehyde (HCHO), and total volatile organic compounds (TVOCs)), and the measurements of biological indicators (bacteria, fungi, *Legionella*). In the reported case, air exchange rates (AERs) were measured by the concentration-decay method using metabolic CO_2 as the tracer gas. The IAQ audit commences with the collection and analysis of the available architectural, mechanical and electrical drawings follows by the walkthrough inspection in order to verify and update the information provided by the building owner or responsible agent, as well as observation for any apparent or potential pollutant sources, occupant's activities and complaints, swift verification of CO_2 levels in the building, pre-evaluation of the hygienic and maintenance conditions of the HVAC systems, and collection of additional information which is deemed necessary for an adequate audit planning.

All collected information on the building and its HVAC systems, including during the walkthrough inspection, is considered to determine the quantity and locations of the required sampling points, a crucial task for the suitable planning of the measuring campaign. The next stage of the audit involves the measurement of the specified indicators, followed by the evaluation phase. In this phase, the measured data will be analyzed and compared with standards/regulations specified limits and the sources of IAQ problems will be identified, with the help of an integral correlation between all indicators measured and information acquired. Finally a set of corrective actions will be recommended to the building owner/manager.

Table 1
Number of measuring points in each zone of the hotel building.

Level	Zone	Location description	Area (m^2)	Max. occupancy	HVAC system	No. of measuring points
−1	A	Restaurant	147	100	AHU3	2
	B	Conference room 1	120	110	AHU2 and MEF4	2
	C	Conference room 2	99	60	AHU4 and MEF4	2
Ground	D	Reception and lobby	541	65	AHU1	4
	E	Business centre	31	4	AHU1 and split	1
1–7	F	Rooms and suites	3332	2 per room	MEFs	15
Roof	G	Exterior	–	–	–	1

AHU: air handling unit.
MEF: mechanical exhaust fan.

2.2. Building characteristics

To better illustrate the proposed IAQ audit methodology of hotel buildings, a 4-star hotel building in a city at the central region of Portugal was selected as a case study. This international hotel was built in 1990 and its interior space has been decorated in 1992. It is a twelve-storey building, including four underground levels. The underground levels are mainly the car parking areas, with the exception of −1 level, in which a restaurant, kitchen and 2 conference rooms are situated. Lobby, reception desk and business centre are situated in ground level. The hotel has 120 rooms and 13 suites distributed by 7 floors with a similar architecture, from 1st level to 7th level.

The HVAC system for the whole building is based in a centralized hot/chilled water production system, with a two-pipe distribution and a fan coil unit (FCU) in each guest room. The guest rooms are naturally ventilated: the sole mechanical ventilation element in each one is the exhaust fan at the respective adjacent bathroom. By this way, the fresh air supplied to the rooms and suites comes in by infiltration through the window frames and from the corridor through the door slits, strongly promoted by the bathroom mechanical exhaust fan. The ground level (lobby, reception, etc.) is served by a specific air handling unit (AHU) with a fraction of air recirculation. The air renewal and thermal conditioning for conference and meeting rooms, as well as for the restaurant is provided by all-fresh AHUs.

2.3. Preliminary visit and measurements

2.3.1. Preliminary visit

A walkthrough inspection and checklist was completed for the hotel to document HVAC system operation and hygiene, air intake location, sources of contaminants, building drainage, roof and interior inspection, maintenance, combustion appliances, room area and volume, carpets, special facilities, space usage and other factors. Photos of each visited points were taken. Floor plans and other information regarding the hotel were obtained.

2.3.2. Number and location of sampling points

After the collection of all the mentioned data, an integrated analysis of the hotel building was done to determine the quantity and locations of the sampling points. All spaces of the building with human occupancy were grouped by zones. Accordingly, the hotel building was divided into 7 different zones based on the ventilation system supplying each zone, the type of activity in the zone, thermal loads, and source of emissions.

Brief overview of the zones and number of measuring points, as well as their corresponding HVAC system are presented in Table 1.

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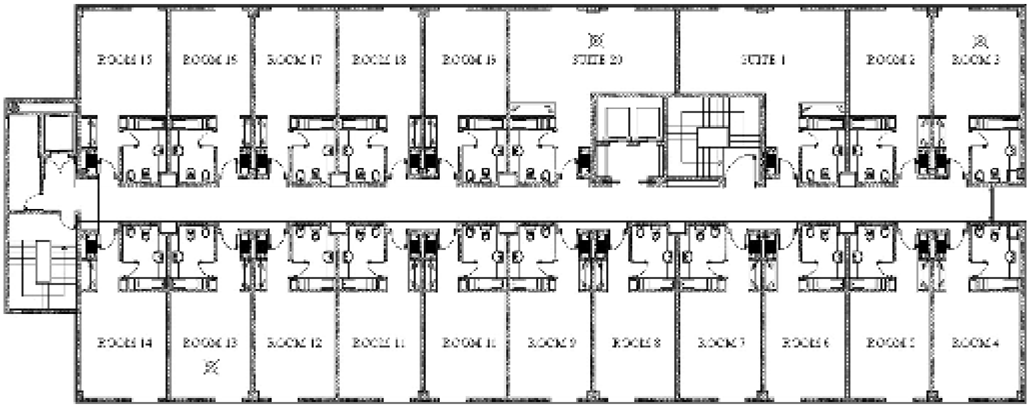

Fig. 1. Typical room level plan (6th level).

The minimum number of sampling points to be considered in each zone was estimated as suggested in the national IAQ guideline (technical note NT-SCE-02, 2009 [17]):

$$N_i = 0.15 \times \sqrt{A_i}, \quad (1)$$

where N_i is the minimum number of sampling points in zone i ($N_i \geq 1$), and A_i is the area of zone i in m^2.

Therefore, for this project the mentioned indicators were measured in 7 zones which encompass 27 points in total. Nevertheless the main area of concern for this IAQ audit is the set of guest rooms, as they are naturally ventilated and lack of good IAQ was much probable. Moreover one of the most important areas of hotels is the guest room where maximum comfort is critical to the success of the hotel [18]. Therefore, we will just provide the result from zone (F) which is the specified zone for guest rooms including suites. Fig. 1 shows the locations of the sampling points for sixth level. Spatial position of sampling points are specified in accordance to the international guideline EN ISO 16000-1 [19]: at least 1 m away from walls in the room, and about 1 m above the floor, since this is the approximate height of the average breathing zone.

2.3.3. Physical indicators

The thermal comfort level of the indoor environment is measured using an indoor climate analyzer DirectSense IAQ (Model IQ610, Graywolf), which allowed measuring the room ambient temperature (dry bulb) and relative humidity, besides the concentration of several chemical pollutants referred in the next section. The concentration of airborne particulate matter (PM_{10}: for particles of size ≤ 10 μm) was measured using an airborne particle counter (Model Handheld 3016 IAQ, LIGHTHOUSE).

Since it was found very probable during preliminary visit that the ventilation rate in the guest rooms was insufficient, AER measurement became inevitable. The AER in the room was measured using the concentration-decay method, in which metabolic CO_2 was selected as the tracer gas [20–24]. The IAQ monitor (Model PS32, SENSOTRON) was used for three days CO_2 measurements.

2.3.4. Chemical indicators

Continuous real-time chemical monitoring of carbon dioxide (CO_2), carbon monoxide (CO), formaldehyde (HCHO), and total volatile organic compounds (TVOCs) was carried out at the predetermined indoor sampling points of each specified zone or group of spaces, at about 1 m above floor level and an outdoor point in close proximity to the fresh air intake point of the AHU, for a period of 15 min at each point. All the above chemical indicators were measured with DirectSense IAQ (Model IQ610, Graywolf), with the exception of formaldehyde (HCHO) which was measured with Formaldehyde Gas Detector (Model FP-30, RIKEN KEIKI Co., Ltd.).

2.3.5. Biological indicators

A portable air sampler (SAS Super IAQ, pb international CO.) for semi-solid medium (Agar plates) with a constant air flow rate of 100 L/min was used to carry out the biological sampling for

Table 2
Detection range and accuracy of the measuring equipment.

Parameter type	Pollutant/Parameter	Equipment	Range	Accuracy
Physical	Temperature	GrayWolf DirectSense IQ-610	−10 °C to 70 °C	1%rdg ± 0.3 °C
	Relative humidity		0–100%	±2%rh <80%rh, ±3%rh >80%rh
	Formaldehyde (HCHO)	Riken Keiki, HCHO Detector FP-30	0–1 ppm	0.08 ppm
Chemical	Carbon dioxide (CO_2)	Sensotron PS32	0–5000 ppm	±(10 + 3% of measured value)
	Carbon monoxide (CO)	GrayWolf DirectSense IQ-610	0–10,000 ppm	±3%rdg ±50 ppm
			0–500 ppm	±2 ppm <50 ppm, ±3%rdg >50 ppm
	Total volatile organic compounds (TVOCs)		5–20,000 ppb	–
Biological	Bacteria	SAS SUPER	Constant	–
	Fungi	IAQ cod. 90993	Airflow rate of 100 L/min	–
	Legionella	Collection of 1 L water in the sterilized PVC bottle	–	–

determining the concentration of bacteria and fungi in the air. The medium used for the collection and further laboratorial culture of bacteria was tryptic soy agar (TSA), while the collection of fungi was made on malt extract agar (MEA). Each of these measurements was taken over a period of 2.5 min to get an air sample of 250 L. After incubation in laboratory under specific temperature conditions, each plate is analyzed and the results of counting are expressed in colony-forming units per cubic meter of air (CFU/m^3). *Legionella* is another biological indicator which should be monitored. An effective sampling of *Legionella* depends upon a correct water sampling, considering relevant factors such as the choice of sampling location, presence of water treatment products or the need to disinfect the sampling point. The sampling criteria are defined in the national IAQ guideline (technical note NT-SCE-02 [17]), regarding namely the minimum number of samples and the typically recommended collection points in the hot-water ductwork.

In order to ensure the suitability of the measuring equipment, the ranges and accuracy of the measurement instruments used in this study are summarized in Table 2.

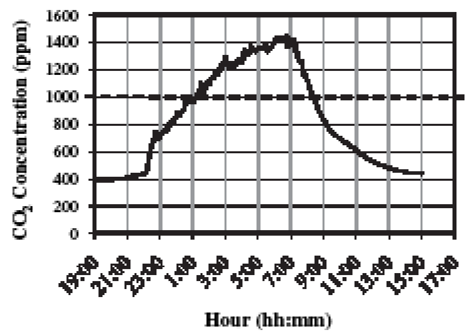

Fig. 2. One-day CO_2 concentration measurement in the selected hotel suite (suite #620).

3. Results and discussion

3.1. Physical indicators

3.1.1. Assessment of the air exchange rate

Since the rooms have no dedicated supply of outdoor air, it was decided to perform a monitoring campaign of CO_2 measurements to assess the adequacy of the AER by infiltration and, if it is the case, find an appropriate remediation action. The IAQ monitor PS32, configured to a sampling interval of 1 min, was left during three days in suite #620.

The fresh air flow rate through a room is usually evaluated using one of the three tracer-gas methods: concentration decay, constant emission or constant concentration method [23]. In this project, the tracer gas concentration-decay method was selected. This is the most basic method for measuring AER and it is used to obtain discrete AER over short periods of time. In this method a certain amount of tracer gas is introduced to the room and then it is mixed with the indoor air to get its uniform concentration in the whole room. Then the gradually decreasing concentration of tracer gas in the air is recorded. In the simplest case the tracer gas may be carbon dioxide introduced in the room in a natural way, through the air exhaled by people staying in that room – metabolic carbon dioxide [20–24]. This was the case in the present study.

The AER (h^{-1}) in this method is determined through the analysis of the decay of CO_2 concentration in the room, after the source of such gas has been stopped, i.e., after the occupants have left the room. So, for a decay period $(t - t_0)$ starting from an assumed uniform CO_2 concentration C_0 in the room, the integration of an overall mass balance leads to

$$C(t) - C_{ext} = (C_0 - C_{ext}) \cdot \exp[-AER(t - t_0)] \tag{2}$$

where $C(t)$ is the observed CO_2 concentration at time t, and C_{ext} is the CO_2 concentration in the outdoor air. All the CO_2 concentrations are expressed in ppm.

Equation (2) can be made explicit for AER (h^{-1}):

$$AER = -\frac{1}{t - t_0} \ln\left(\frac{C(t) - C_{ext}}{C_0 - C_{ext}}\right) \tag{3}$$

The direct estimation of the AER through equation (3) is easy when conditions are stable regarding the fresh air flow rate, the CO_2 concentration in outdoor air and the flow pattern inside the room. However equations (2) and (3) apply to the case of a uni-zone room having air exchanges only with outdoor environment. In the present case, as the room door is very tight and the corridor is most of the time unoccupied, it was concluded that the studied room could be considered a uni-zone compartment. Regarding the uniformity of the distribution of the CO_2 concentration inside the room, it was not possible to put in practice, previous to the decay phase, the recommended procedure of using a fan during a short period to promote a good dilution, on account of the hotel guests privacy issues. Nevertheless, it was latter checked that in a similar room where an equilibrium concentration of 1100 ppm had been achieved after the sleeping period, the spatial variability of CO_2 concentration was in the order of ±15 ppm. In rooms where there is not a strong ventilation flow, spatial non-uniformities of CO_2 concentrations tend to be lower.

A previous smoothing procedure may be recommended to minimize the disturbing influence of imprecision due to the fluctuating feature of the recorded $C(t)$ data, as it is the case of gas analyzers with imprecision higher than ±30 ppm. Parameters were estimated by fitting the logarithm of the concentrations against time. Fig. 2 shows the first day evolution of CO_2 concentration in suite #620, before any remediation action. A curve fitting, with a linear law for a chosen concentration-decay period is shown in Fig. 3, indicating an AER of 0.429 h^{-1}. The value of AER estimated by this method was robust, i.e., regression achieved a correlation coefficient $R = 0.9978$, which means that conditions were quite stable. The represented decay period corresponds to a calm day

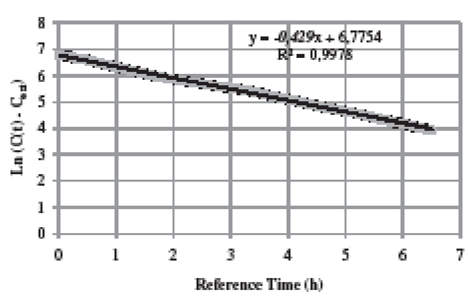

Fig. 3. Linear regression for a chosen concentration-decay period, i.e. when the occupants left the room.

Table 3
Measurement of air exchange rate (AER) and fresh air flow rate (m^3/h/occupant).

Location	Volume (m^3)	Number of occupants	AER (h^{-1})	Fresh air flow rate per occupant (m^3/h/occupant)
Suite #620	93.25	2	0.429	20
Portugal national IAQ guideline	–	–	–	Minimum required: 30 m^3/h/occupant

with low wind velocity ($v < 2$ m/s), thus it represents the worst case regarding AER conditions in the studied room.

It is seen from Table 3 that by the 0.429 h^{-1} AER, the amount of fresh air (coming into the room by infiltration) provided to suite #620 in the considered decay period was 20 m^3/h/person, which is lower than the minimum requirement stated by national IAQ regulation (RSECE [14]) for design project of hotel rooms in new buildings which is 30 m^3/h/occupant.

Consequently, it was suggested to the hotel technical management to keep the bathroom mechanical exhaust fan working during the night period. In Fig. 4 the time evolution of CO_2 concentration during a day after prescribing the new control policy for bathroom mechanical exhaust fan is presented. Accordingly, the fresh air flow rate raised enough to keep the CO_2 concentration within an acceptable level during the whole period with the total occupancy of the room, regarding the second compliance criterion for CO_2 in existing building, based on national IAQ guideline [17], which indicates an average CO_2 value lower than 1500 ppm, during the whole occupancy period (see Section 3.2.1 for further details).

3.1.2. Evaluation of thermal comfort

The measured thermal comfort parameters during 2 days measurement campaign (28–29 March 2009) are listed in Table 4. The average air temperature recorded in each guest room ranged from 23 to 24.0 °C. This is within the recommended range according to ASHRAE design criteria [18]. The temperature in the cold season (winter) should vary between 23 °C and 24 °C, in the hot season (summer) between 23 °C and 26 °C, relative humidity should be between 30% and 35% in winter, 50% and 60% during summer and air velocity should not exceed 0.2 m/s in the guest room. Too cold temperature will not only make guests uncomfortable, it will also result in more energy consumption in air-conditioning. The average relative humidity of each room ranged

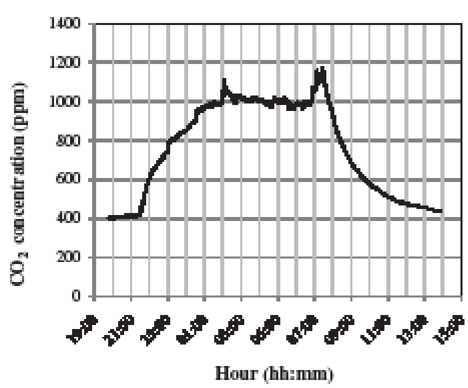

Fig. 4. CO_2 measurement with the bathroom mechanical exhaust fan working during the night period.

Table 4
Thermal comfort parameters.

Location	Air temperature (°C)	Relative humidity (%)
Suite #620	23.8	34.6
Room #613	24	31.5
Room #603	23.9	34
Outside air	14	55
ASHRAE guideline	23–24 (winter) 23–26 (summer)	30–35 (winter) 50–60 (summer)

from 31.5% to 35%, which is within the recommended range (30–35%). The mean air velocity in the rooms was not measured because it was clearly found unnecessary.

3.1.3. Evaluation of particulate pollution

The recommended threshold level for the concentration of suspended particulate matter (PM_{10}) in indoor air is 150 μg/m^3 in Portugal [14]. Table 5 shows the measured values of indoor concentration of PM_{10}, which overcome the threshold level in two of the monitored rooms of the 6th floor. It should be mentioned that these measurements were conducted shortly after the cleaning operation of the rooms. Further tests proved an increase of the PM_{10} concentration after vigorous walking in the rooms, which suggested that the detected suspended particulate matter originated from the floor carpet, where it was somehow deposited. A recommendation for implementing an improved technique and more frequent cleaning was given to the hotel management.

3.2. Chemical indicators

3.2.1. Carbon dioxide (CO_2)

The concentration of carbon dioxide in the specified sample points varied between locations, and reached values as high as 1710 ppm. During night hours, the concentration level of CO_2 increased due to the constant metabolic emission by the guests in the rooms and the AER revealed to be insufficient. Regarding the CO_2 concentration, the verification of compliance with the national regulation limit value (1000 ppm) must take into account the actual occupancy of the room. For this purpose, the technical note NT-SCE-02, 2009 [17] suggests the following criterion:

$$([CO_2]_{MedT} - [CO_2]_{Ext}) \times \frac{N_{ocup.max}}{N_{ocup.}} + [CO_2]_{Ext} \leq [CO_2]_{MR} \quad (4)$$

where $[CO_2]_{MR}$ is reference limit value of CO_2 concentration, 1800 mg/m^3 (corresponding to 1000 ppm at standard pressure and 25 °C [10]), $[CO_2]_{Ext}$ is the CO_2 concentration in the outdoor air (400 ppm for this case), $[CO_2]_{MedT}$ is time-averaged concentration of CO_2 in each sampling point in ppm, $N_{ocup.max}$ is maximum allowed number of occupants in the room or space, N_{ocup} is the actual number of occupants during the measurements.

For the case of existing buildings, if this first criterion is not fulfilled, a second one is recommended that allows an increase of 50% of the threshold level, but implies measuring and averaging the

Table 5
Measurement of suspended particulate matter.

Location	PM_{10} (μg/m^3)
Suite #620	194
Room #613	59
Room #603	159
Outside air	84
Portugal national IAQ guideline limit	150

CO_2 over the full period of occupancy. This second criterion may be expressed as:

$$([CO_2]_{MedT} - [CO_2]_{Ext}) \times \frac{N_{ocup.max}}{N_{ocup.}} + [CO_2]_{Ext} \leq [CO_2]_{MR} \times 1.5 \quad (5)$$

where $[CO_2]_{MedT}$ is now the time-averaged CO_2 concentration for the extended period.

The time-averaged concentration of CO_2 is calculated by the following expression:

$$[CO_2]_{MedT} = C_T = \frac{\sum \Delta t_i \times C_i}{T} \quad (6)$$

where C_i in ppm is the pollutant concentration at time t_i, Δt_i is the sampling measurement period, and T is the total measurement period.

Fig. 2 shows the time evolution of the measured CO_2 concentration in suite #620 occupied by only one guest. It may be concluded that the guest entered the suite at 22:15 and left at about 07:10. Thus, taking $\Delta t_i = 1$ min and applying expression (6) in this occupancy period, we obtain $[CO_2]_{MedT} = 1128$ ppm. Considering $N_{ocup.max.} = 2$ for suites, the left hand side of expressions (4) and (5) will become:

$$([CO_2]_{MedT} - [CO_2]_{Ext}) \times \frac{N_{ocup.max}}{N_{ocup.}} + [CO_2]_{Ext} = 1856 \text{ ppm},$$

which exceeds by 86% and 24% the limits for the first and the second compliance criteria, respectively (i.e., 1000 ppm and 1500 ppm).

After implementing the prescribed control policy for bathroom mechanical exhaust fan, as shown in Fig. 4, the average concentration is $[CO_2]_{MedT} = 927$ ppm during the occupancy period from 21:30 to 7:30. Thus the left hand side of expression (5) will become:

$$([CO_2]_{MedT} - [CO_2]_{Ext}) \times \frac{N_{ocup.max}}{N_{ocup.}} + [CO_2]_{Ext} = 1454 \text{ ppm}.$$

Therefore the corrective action led to compliance of the CO_2 concentration with the second criterion.

3.2.2. *Carbon monoxide (CO)*

The maximum reference value for CO concentration is 12.5 mg/m^3, corresponding to 10 ppm according to national IAQ regulation [14]. In this study (guest rooms with no smoking activity) the measured CO concentration ranged from 0.0 to 0.6 ppm, values that are well below the recommended thresholds.

3.2.3. *Formaldehyde (HCHO)*

The concentrations of formaldehyde measured in this study were below 0.01 ppm, therefore in compliance with the national regulation (threshold level of 0.08 ppm). Generally, the high concentrations of formaldehyde are attributed to the materials used for interior decoration, as well as the emission from the detergents and cleaning agents.

3.2.4. *Total volatile organic compounds (TVOCs)*

The threshold value for total volatile organic compounds in the indoor environment in Portugal is 0.6 mg/m^3 corresponding to 0.26 ppm (referred to isobutylene) or 0.16 ppm (referred to toluene) [14]. It is observed that the maximum concentrations of TVOCs in the selected rooms are 0.2, 0.17 and 0.18 mg/m^3, and these are below the threshold value. Generally, the high concentrations of TVOCs in the hotel rooms are attributed to the emission from the detergents and cleaning agents used by the housekeepers when cleaning the room.

Table 6
Measurement results for the chemical indicators (CO_2, CO, HCHO and TVOCs).

Location		CO_2 (ppm)	CO (ppm)	Formaldehyde (HCHO) (ppm)	TVOCs (mg/m^3)
Suite #620		469	0	<0.01	0.2
Room #613		426	0	<0.01	0.17
Room #603		488	0.6	<0.01	0.18
Outside air		396	0	<0.01	0.32
Portugal national IAQ guideline limit	ppm	1000	10	0.08	0.16
	mg/m^3	1800	12.5	0.1	0.6

The data obtained from the measurements of the chemical indicators concentrations in the selected rooms are shown in Table 6. It should be remarked that these measurements were carried out with no effective occupants in the rooms; therefore the CO_2 values are not valid for compliance verification purposes.

3.3. *Biological indicators*

The recommended threshold value for total concentration of bacteria and fungi in the indoor air is 500 CFU/m^3 in Portugal [14]. As for *Legionella*, the maximum limit value is 100 CFU/L of water, the sampling criteria being defined in the technical note NT-SCE-02 [17], regarding namely the minimum number of samples and the typically recommended collection points in the hot-water ductwork. In the present audit, besides the purge of the hot-water storage tank and the return collector, 1 L samples were collected from ten showers (in rooms selected randomly), plus one at each of the staff male and the female washrooms. The measured data for selected rooms are shown in Table 7 and these results indicate that the indoor air microbial pollution in guest rooms is well below the limit values. However, a generalized contamination by *Legionella* was detected in the hot-water circuit, although with no presence of the pathogenic species (*Legionella pneumophila*). This imperatively determined an immediate overall thermal decontamination procedure, of which the effectiveness was checked out by further water sampling and analysis two weeks later.

3.4. *Discussion*

In the course of this audit, some problems or situations with risk for good IAQ in the hotel building were identified, such as: (1) excessive CO_2 concentration in the guest rooms during the period of occupancy (insufficient ventilation); (2) too high particle concentration in some rooms (after the housekeeping operation), due to dispersion of dust deposited on carpets; (3) contamination by non-pathogenic *Legionella* of the sanitary hot-water circuit; (4) signs of fungi growing on the inner surface of a wall (due to infiltrations); (5) degradation of the inner wall insulation, of the condensate tray and of the filter cassettes of the main AHU1 (serving the lobby, the reception and other spaces at the level 0) and poor hygienic conditions due to inefficient filtration of the outdoor air; (6) Poor filtration effectiveness in all AHUs; (7) Deterioration and dirtiness in the condensate trays of the rooms fan coil units, due to bad drainage and difficult access for maintenance.

Table 7
Measured concentrations of microbial pollutants.

Location	Total bacteria (CFU/m^3)	Total fungi (CFU/m^3)	*Legionella* (CFU/L water)
Suite #320	131	6.5	2271
Suite #620	140.5	3.5	236
Portugal national IAQ guideline	500	500	100

APPENDIX C PAPER PUBLISHED AT BUILDING AND ENVIRONMENT JOURNAL: INDOOR AIR QUALITY IMPLEMENTATION IN A HOTEL BUILDING IN PORTUGAL

These findings led to a set of recommendations for improvement of IAQ conditions, namely:

1. keep the mechanical exhaust fan of the bathrooms working during the night period (to guarantee a minimum level of outdoor air intake by infiltration);
2. improve the methodology and increase the frequency of cleaning/washing the room carpets;
3. retrofit of the sanitary hot-water network with stainless steel ducts;
4. retrofit some parts of the building envelop, to prevent water infiltration and condensation on the inner surfaces;
5. install an efficient filtration section at the fresh air intake of the smaller AHUs;
6. replace the AHU1 by a new one, with energy recovery, efficient filtration, a plug fan and the possibility of variable, demand controlled air flow rate;
7. replacement of the condensate trays of FCUs.

It is necessary to state that according to the energy certification of building program in Portugal, the analyzed hotel building is categorized as "A" class. However, as it was documented above, there are some problems related to the indoor air quality in the building. Fortunately in Portugal it is mandatory to have IAQ audit along with the energy certification of large buildings. Thus the hotel manager was mandated to solve the reported IAQ problems. Finally, the building manager was sensitized for the importance of guaranteeing good IAQ in the building, which depends greatly on the adequate operation and planned maintenance of the HVAC systems.

The result from IAQ audit shows the necessity and the convenience of performing an IAQ audit along with the energy audit of buildings.

4. Conclusion

Hotel buildings are expected to fulfil a variety of requirements, applicable codes and standards, and environmental and community impact rules. Among these requirements, IAQ is typically addressed through compliance with only minimum code requirements, which are based on industry consensus standards. Yet IAQ affects occupant health, comfort, and productivity, and in some cases even building usability, all of which can have significant economic impacts for building owners/managers and occupants/guests.

While hotel manager/owner and building professionals may recognize the importance of IAQ, they often do not acknowledge how design, construction decisions and control routines can result in IAQ problems. In addition, they may assume that achieving a high level of IAQ is associated with premium costs and novel or even risky technical solutions. In other cases, they may employ individual measures thought to provide good IAQ, such as increased outdoor air ventilation rates or specification of lower emitting materials, without a sound understanding of the project-specific impacts of these measures or a systematic assessment of IAQ priorities. On the other hand little research has been concerned to the IAQ of hotel buildings up to now.

This study presented practical information and guideline on how to establish and conduct the comprehensive IAQ audit approach for hotel buildings, based on Portugal national laws. The procedure presented for IAQ audit of hotel buildings proved to be simple and comprehensive. Beyond the preliminary visit, the systematic approach involves the measurement of physical parameters, the monitoring of the concentrations of selected indoor air pollutants, and the measurements of airborne fungi and bacteria. Continuous monitoring of metabolic CO_2 revealed to be a useful method to have a better knowledge of the AER in the studied space and to check the effectiveness of the implemented corrective measures.

In particular, the application of the procedure to a selected hotel building enabled to survey the IAQ performance of the hotel building.

The conclusion is that such a methodology is suitable for short period assessment on hotel building stock, being very useful for finding the appropriate remediation actions to solve the IAQ problems in such buildings. Moreover, the results demonstrated the feasibility of the approach, thus encouraging further extensions and/or improvements and application to other building types, such as office buildings and schools.

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APPENDIX D PAPER PUBLISHED AT ENVIRONMENTAL MONITORING ASSESSMENT JOURNAL: A SYSTEMATIC INDOOR AIR QUALITY AUDIT APPROACH FOR PUBLIC BUILDINGS

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A systematic indoor air quality audit approach for public buildings

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Abstract Good indoor air quality (IAQ) in buildings provides a comfortable and healthy environment for the occupants to work, learn, study, etc. Therefore, it is important to ascertain the IAQ status in the buildings. This study is aimed to establish and demonstrate the comprehensive IAQ audit approach for public buildings, based on Portugal national laws. Four public buildings in Portugal are used to demonstrate the IAQ audit application. The systematic approach involves the measurement of physical parameters (temperature, relative humidity, and concentration of the suspended particulate matter), monitoring of the concentrations of selected chemical indicators [carbon dioxide (CO_2), carbon monoxide, formaldehyde, ozone, and total volatile organic compounds], and the measurements of biological indicators (bacteria and fungi). In addition, air exchange rates are measured by the concentration decay method using metabolic CO_2 as the tracer gas. The comprehensive audits indicated some situations of common IAQ problems in buildings, namely: (1) insufficient ventilation rate, (2) too high particle concentration; and (3) poor filtration effectiveness and hygienic conditions in most of the air handling units. Accordingly, a set of recommendations for the improvement of IAQ conditions were advised to the building owner/managers.

Keywords Indoor air quality (IAQ) · Air exchange rate (AER) · Indoor air pollutants · Metabolic CO_2

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Introduction

Indoor air pollution is currently a major public health problem given the fact that most of the urban populations spend more than 80 % of their time indoors and that various airborne pollutants can cause serious health problems. Fanger (2006) claimed that the incidence of allergic and asthmatic diseases has doubled in developed countries over the past two decades. Bornehag et al. (2005) believed that the worsening of indoor air quality (IAQ) is a primary reason for the increment in these diseases. IAQ has declined because of comprehensive energy conservation campaigns and because high-energy prices have motivated people to tighten their buildings and reduce the rate of ventilation, so that the air renewal in many premises is at historically low level.

On the other hand, the European Parliament and Council approved a directive on the energy performance of buildings 2002/91/EC (EPBD) (European Union 2002), which introduced the obligation of energy certification of buildings. However, it does not mandate IAQ assessment of buildings. Portugal, as one of the European Union member states, has adopted a series of measures to implement the EPBD into the national law (SCE 2006; RSECE 2006; RCCTE 2006) and in the nonresidential regulations (RSECE 2006). IAQ periodic audits of existing buildings became mandatory. Nevertheless, it is not the case for most of the member countries.

In this scope, a comprehensive IAQ audit methodology along with energy audit of buildings should be established to identify the indoor air problems. Although some IAQ monitoring methods have been developed in different countries, most of them involve a large amount of resources and manpower in terms of conduction of the measurements, interpretation of the data, on-site operation of the equipment, sophisticated specifications of the application, as well as calibration and regular maintenance of the instruments.

Hence, the purpose of this study is to develop and demonstrate a comprehensive IAQ audit methodology for public buildings that does not demand a large amount of resources and manpower. The data collected from this approach can be used to assess the air quality in buildings and to identify the indoor air problems and consequently reduce the health risks.

Apart from the introduction, the paper is structured in three more sections. The second section is devoted to the proposed IAQ audit methodology and its application on four public buildings. It is followed by the discussion on the results of methodology application on case studies. Finally, the "Discussion" section summarizes the main conclusions drawn up from this paper.

Methods

IAQ audit methodology

The proposed IAQ audit follows a systematic approach (shown in Fig. 1) with portable equipment, involving the measurement of physical parameters [dry bulb temperature, relative humidity (RH), and the concentration of the suspended particulate matter (PM10)], the monitoring of the concentrations of selected chemical indicators [carbon dioxide (CO_2), carbon monoxide (CO), formaldehyde (HCHO), ozone (O_3), and total volatile organic compounds (TVOCs)], and the measurement of biological indicators (bacteria and fungi). In addition, air exchange rates (AERs) were measured by the concentration decay method using metabolic CO_2 as the tracer gas where it was necessary.

The IAQ audit commences with the collection and analysis of the available architectural, mechanical, and electrical drawings followed by the preliminary visit in order to verify and update the information provided by the building owner or responsible agent, as well as observation for any apparent or potential pollutant sources, occupant's activities and complaints, swift verification of CO_2 levels in the building, pre-evaluation of the hygienic and maintenance conditions of the heating, ventilating, and air conditioning (HVAC) systems, and collection of additional information which is deemed necessary for an adequate audit planning. All collected information on the building and its HVAC systems is considered to determine the quantity and locations of the required sampling points, a crucial task for the suitable planning of the measuring campaign.

The next stage of the audit involves the measurement of the specified indicators, followed by the evaluation phase. In this phase, the measured data will be analyzed and compared with limits specified by standards/regulations, and the sources of IAQ problems will be identified, with the help of an integral correlation between all indicators measured and information acquired. Finally, a set of corrective actions will be recommended to the building owner/manager.

Building characteristics

Four buildings in Portugal, of four different uses (office, hotel, school, and library), were selected as case studies (Table 1). The selected buildings were diverse, ranging from 11 to 70 years of age. The main areas of interest for this IAQ audit were the administration rooms of the office building, hotel guest rooms, school classrooms, and library reading rooms. All buildings were equipped with mechanical ventilation with the exception of hotel guest rooms which were naturally ventilated.

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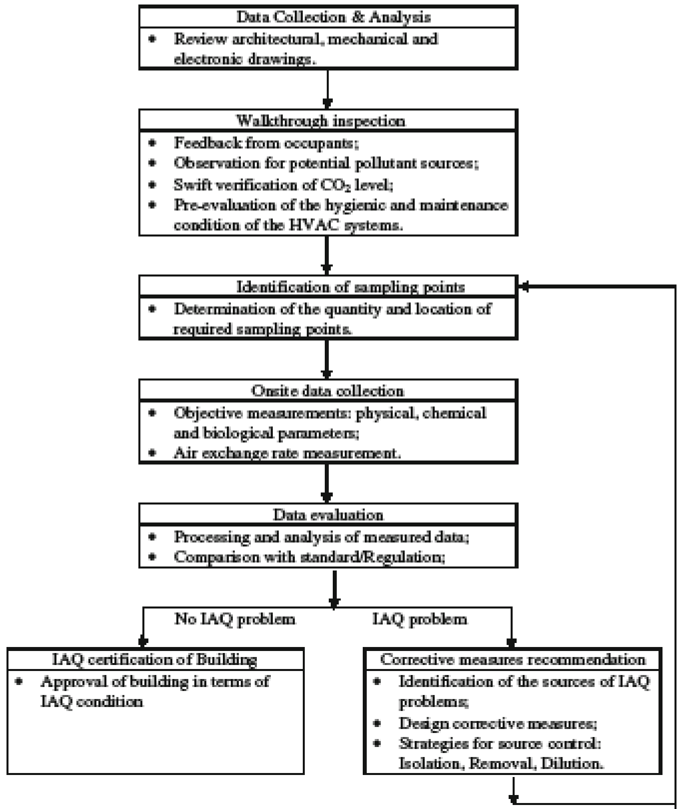
Fig. 1 IAQ audit methodology



Preliminary visit and measurements

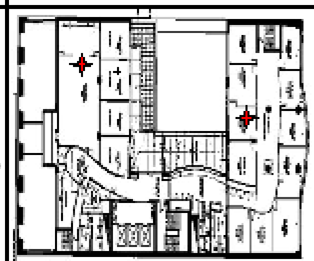
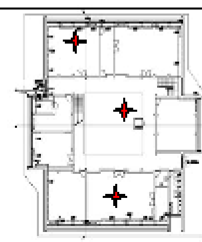
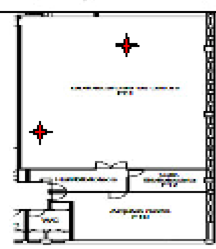
Preliminary visit

A walkthrough inspection and checklist was completed for the four buildings to document HVAC system operation and hygiene, air intake location, sources of contaminants, building drainage, roof and interior inspection, maintenance, combustion appliances, room area and volume, carpets, special facilities, space usage, and other factors. Photos of each visited places were taken. Additional information regarding the buildings was obtained.

Number and location of sampling points

All spaces of the buildings with human occupancy were grouped by zones. A measuring zone is here understood as a set of spaces with similar characteristics, in compliance with the following criteria: they should (a) all be ventilated with the same air diffusion strategy (e.g., mixing or displacement ventilation) and be served by the same air handling unit (AHU); (b) have similar activities, thermal loads and pollutant emissions, and similar layout; and (c) spaces with complaint records or hosting more requiring occupants (e.g., children or elderly people) should form a specific measuring zone.

Table 1 Summary of the building characteristics

Building ID	Building type	Date built	Floor plan & measured spot	Basic data	
1	Office	1940		No. of building levels	9
				Point of interest	Office rooms
				HVAC type	Main fan distribution, some unit ventilators AC
2	Hotel	1990		No. of building levels	12
				Point of interest	Guest rooms
				HVAC type	FCU, NV
3	School	1972		No. of building levels	3
				Point of interest	Class rooms
				HVAC type	AHU
4	Library	1999		No. of building levels	1
				Point of interest	Reading room
				HVAC type	AHU

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The minimum number of sampling points N_i to be considered in each zone i with area A_i (in square meter) was estimated as suggested in the national IAQ guideline (Technical Note NT-SCE-02 2009):

$$N_i = 0.15 \times \sqrt{A_i}, (N_i \geq 1). \quad (1)$$

Spatial position of sampling points is specified in accordance to the international guideline EN ISO 16000–1 (2004): at least 1 m away from walls in the room and about 1 m above the floor, since this is the approximate height of the average breathing zone. Locations of sampling points in each case study are marked with red stars in Table 1.

Physical indicators

The thermal comfort level of the indoor environment is measured using an indoor climate analyzer DirectSense IAQ (model IQ610, GrayWolf), which allowed measuring the room ambient temperature (dry bulb) and relative humidity, besides the concentration of several chemical pollutants referred in the next section. The concentration of airborne particulate matter (PM10: for particles of size ≤10 μm) was measured using an airborne particle counter (model Handheld 3016 IAQ, Lighthouse).

Air exchange rates

The fresh air flow rate through a room is usually evaluated using one of the three tracer gas methods: concentration decay, constant emission, or constant concentration method (Charlesworth 1988). In this project, the tracer gas concentration decay method was selected. This is the most basic method for measuring AER and it is used to obtain discrete AER over short periods of time. In this method, a certain amount of tracer gas is introduced to the room and then it is mixed with the indoor air to get its uniform concentration in the whole room. Then, the gradually decreasing concentration of tracer gas in the air is recorded. In the simplest case, the tracer gas (CO_2) may be introduced in the room in a natural way, through the air exhaled by people staying in that room—metabolic carbon dioxide (Charlesworth 1988; Persily 1997; Roulet and Foradini 2004; Godwin and Batterman 2007; Coley and Bersteiner 2000; Naydenov et al. 2004; Corgnati et al. 2011).

The AER (in hours) in this method is determined through the analysis of the decay of CO_2 concentration in the room, after the source of such gas has been stopped, i.e., after the occupants have left the room. So, for a decay period $(t-t_0)$ starting from an assumed uniform CO_2 concentration C_0 in the room, the integration of an overall mass balance leads to:

$$C(t) - C_{ext} = (C_0 - C_{ext}) \cdot \exp[-\mathrm{AER}(t - t_0)], \quad (2)$$

where $C(t)$ is the observed CO_2 concentration at time t, and C_{ext} is the CO_2 concentration in the outdoor air. All the CO_2 concentrations are expressed in milligrams per cubic meter. Equation (2) can be made explicit for AER. Finally, AER may be estimated by fitting the logarithm of the concentrations against time (Asadi et al. 2011).

Chemical indicators

Continuous real-time chemical monitoring of CO_2, CO, HCHO, O_3, and TVOCs was carried out at the predetermined indoor sampling points of each specified zone or group of spaces, at about 1 m above floor level and at an outdoor point in close proximity to the fresh air intake of the AHU, for a period of 15 min at each point. All the above chemical indicators were measured with DirectSense IAQ (model IQ610, GrayWolf sensing solution), with the exception of HCHO which was measured with a formaldehyde gas detector (model FP-30, Riken Keiki Co., Ltd.).

Biological indicators

A portable air sampler (SAS Super IAQ, PB International Co.) for semisolid medium (agar plates) with a constant airflow rate of 100 L/min was used to carry out the biological sampling for determining the concentration of bacteria and fungi in the air. The medium used for the collection and further laboratory culture of bacteria was trypticase soy agar, while the collection of fungi was made on malt extract agar. Each of these measurements was taken over a period of 2.5 min to get an air sample of 250 L. After incubation in laboratory under specific temperature conditions, each plate is analyzed and the results of counting are expressed in colony-forming units per cubic meter of air (CFU/m^3). *Legionella* is another biological indicator which should be monitored, taking 1 L samples of hot water (HW) circuits or reservoirs potentially generating sprays: from the purge valve of each storage tank and of the return collector and from supply terminals. With particular use for buildings having a great number of showers (e.g., hotels, hospitals, etc.), the Technical Note NT-SCE-02 (2009) recommends a minimum number of water-sampling points to be estimated as:

$$N_i = 0.75 \times \sqrt{N_t}, \quad (3)$$

where N_t is the number of water terminals in each zone i. The selection of the sampling points should include primarily showers that (a) are not operated daily and (b) are most distant from the hot water storage tank or heating equipment.

In order to ensure the suitability of the measuring equipments, the ranges and accuracy of the measurement instruments used in this study are summarized in Table 2.

Results and discussion

Physical indicators

Evaluation of thermal comfort

The thermal comfort parameters are presented in Table 3. The air dry bulb temperature recorded in specified measuring points ranged between 24 and 26°C and the RH ranged between 32 and 60 % and all—except building "3" (school)—achieved the comfort range (20 to 26°C and 20 to 60 % RH) as per the recommendations of ASHRAE (1993).

Evaluation of particulate pollution

The recommended threshold level for the concentration of PM10 in indoor air in Portugal is 0.15 mg/m^3 (RSECE 2006). Table 1 shows the measured values of indoor concentration of PM10, which overcome the threshold level in all buildings except building "4" (library). In the case of building "1" (office), the pollution source was the smoking activity (allegedly sporadic) in the director's office. The excessive indoor air particle concentration in some of the hotel rooms was due to accumulation in the floor carpet associated with enhanced dispersion by people walking. The vacuum cleaner used for daily cleaning was a top model equipped with a HEPA filter; therefore, more frequent washing of the carpets was recommended (once every 3 months). As for the school building, it was concluded that the current wiping process of the classroom floors should be avoided because it leaves a significant amount of particulate matter deposited, which is later disseminated by the students' natural activity, mainly on entrance and leaving the room. Vacuum cleaning method was recommended.

Chemical indicators

Carbon dioxide

CO_2 levels ranged widely and exceeded 1,800 mg/m^3 (corresponding to 1,000 ppm at standard pressure and 25°C) in some measuring points (Table 1). Peak levels reached 1,785, 2,005, 3,390, and 2,677 mg/m^3 in buildings "1" to "4", respectively. Accordingly, high CO_2 levels were found in all buildings except building "1" (office), which led us to further investigate for the sources of higher values.

Regarding the CO_2 concentration, the verification of compliance with the national regulation limit value (1,800 mg/m^3) must take into account the actual occupancy of the space. For this purpose, the technical note (NT-SCE-02 2009) suggests the following criterion:

$$([CO_2]_{MedT} - [CO_2]_{Ext}) \times \frac{N_{occup.max.}}{N_{occup.}} + [CO_2]_{Ext} \leq [CO_2]_{MR}, \quad (4)$$

where $[CO_2]_{MR}$ is maximum reference value of CO_2 concentration, 1,800 mg/m^3, $[CO_2]_{Ext}$ is the CO_2 concentration in the outdoor air, and $[CO_2]_{MedT}$ is time-averaged concentration of CO_2 in each sampling point; $N_{occup.\ max.}$ is the maximum allowed number of occupants in the room or space; and $N_{occup.}$ is the actual number of occupants during the measurements.

For the case of existing buildings, if the first criterion is not fulfilled, a second one is recommended that allows an increase of 50 % of the threshold level, but implies measuring and averaging the CO_2 over the full daily period of occupancy. Since the first criterion was not fulfilled in buildings "2" to "4," the second criterion was evaluated. The result is presented in Table 1. There is no case with more than 2,700 mg/m^3 of CO_2 average concentration during the whole occupancy

Table 2 Detection range and accuracy of the measuring equipment

Parameter type	Pollutant/parameter	Equipment	Measuring principle	Range	Accuracy
Physical	Temperature	GrayWolf DirectSense IQ-610	Thermal resistance Pt 100	−10 to 70°C	1 %rdg±0.3°C
	Relative humidity		Capacitive probe	0 to 100 %	±2 %rh <80 %rh, ±3 %rh >80 %rh
	PM10	Handheld 3016 IAQ	Laser diode particle counter	0.3–25 µm	Counting efficiency, 50 % at 0.3 µm
Chemical	Carbon dioxide (CO_2)	Sensotron PS32	Non-dispersive infrared	0 to 5,000 ppm	± (10 ppm+3 % of measured value)
	Carbon dioxide (CO_2)	GrayWolf DirectSense IQ-610	Non-dispersive infrared	0 to 10,000 ppm	±3 %rdg±50 ppm
	Carbon monoxide (CO)		Electrochemical probe	0 to 500 ppm	±2 ppm, <50 ppm; ±3 %rdg, >50 ppm
	Total volatile organic compounds (TVOCs)		Photoionization detector (PID)	5 to 20,000 ppb	–
	Ozone (O_3)		Electrochemical probe	0 to 1 ppm	0.01 ppm
	Formaldehyde (HCHO)	Riken Keiki, HCHO detector	Photoelectrical photometry with detection tablet	0 to 1 ppm	0.08 ppm
Biological	Bacteria	SAS Super IAQ cod. 90593	CFU counting in a microscope after incubation period	Constant airflow rate of 100 L/min	None
	Fungi				None
	Legionella	Collection of 1 L water in the sterilized PVC bottle	CFU counting in a microscope on a plate after sample concentration	Non-dispersive	None

%rdg percentage of reading, *%rh* percentage of relative humidity

Table 3 Basic characteristics of buildings, temperature, relative humidity, PM10, CO_2, CO, HCHO, TVOCs, O_3, and bacteria and fungi concentration

Building ID	Zone of measurement	Date studied (M/Y)	Measuring point ID	Max. occupancy	Temperature (°C)	Relative humidity (%)	PM10 (mg/m^3)	CO_2 (mg/m^3)	CO_2 2nd criterion LHS	CO (mg/m^3)	HCHO (mg/m^3)	TVOCs (mg/m^3)	O_3 (mg/m3)	Bacteria (CFU/m^3)	Fungi (CFU/m^3)
1 (office)	Office rooms	6/10	111	2	26	58	0.25	1,439	–	0.00	<0.01	2.33	0.00	–	–
			121	3	25	57	0.12	1,255	–	0.00	<0.01	2.50	0.00	352	188
			122	3	26	58	0.48	1,750	–	0.00	<0.01	4.10	0.07	–	–
			131	6	25	59	0.10	1,617	–	0.00	<0.01	2.45	0.00	–	–
			141	3	25	58	0.39	1,610	–	0.00	<0.01	0.00	0.00	164	44
			151	2	25	60	0.36	1,785	–	3.10	<0.01	0.01	0.00	354	64
			1ext1	–	15	80	0.14	826	–	0.80	<0.01	4.72	0.00	112	120
2 (hotel)	Guest rooms	3/09	261	2	24	35	0.19	1,850	–	0	<0.01	0.20	0.00	131	6.5
			262	2	24	32	0.06	1,700	–	0	<0.01	0.17	0.00	–	–
			263	2	24	34	0.16	2,005	3,337	0.6	<0.01	0.18	0.00	140.5	3.5
			2ext1	–	14	55	0.08	750	–	0	<0.01	0.32	0.04	212	156
3 (school)	Classrooms	5/10	311	23	24	64	0.82	1,259	–	1.6	<0.01	0.01	0.00	–	–
			312	24	27	63	0.82	2,553	3,521	2.1	<0.01	0.00	0.00	450	340
			313	27	26	58	0.37	1,955	–	2	<0.01	0.00	0.00	–	–
			321	23	26	66	0.54	2,319	–	1.7	<0.01	0.01	0.00	462	416
			322	21	27	65	0.93	3,390	3,675	2	<0.01	0.01	0.00	–	–
			323	29	22	89	0.36	2,166	–	0.8	<0.01	0.02	0.00	–	–
			3ext1	–	17	94	0.06	750	–	1	<0.01	0.02	0.00	100	480
4 (library)	Reading room	6/10	411	–	26	58	0.07	2,457	–	2.22	<0.01	0.04	0.00	–	–
			412	90	26	58	0.05	2,505	2,665	1.98	<0.01	0.00	0.00	62	465
			4ext1	–	32	48	0.07	869	–	2.81	<0.01	0.00	0.00	110	480

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period in building "4"; therefore, the library reading room is in compliance with the second criterion. However, CO_2 concentrations in buildings "2" and "3" exceeded the limit value by 24 and 30 %, respectively. Therefore, AER measurements were carried out. It is seen that the AER in the hotel room is 0.429 h^{-1}, corresponding to 20 m^3/h of infiltrated fresh air per person, which is lower than the minimum requirement stated by the national IAQ regulation (RSECE 2006) for design project of hotel rooms in new buildings (30 m^3/h/occupant). Consequently, it was suggested to the hotel technical management to keep the bathroom mechanical exhaust fan working during the night period, which led to compliance of CO_2 concentration according to second criterion for existing buildings.

Carbon monoxide

The CO concentration should not exceed 12.5 mg/m^3 (10.5 ppm) according to national IAQ regulation (RSECE 2006). In this study (buildings with no smoking activity), the measured CO concentration ranged from 1.44 to 3.10 mg/m^3—values that are well below the recommended thresholds.

Formaldehyde

The concentrations of formaldehyde measured in this study were below 0.01 ppm—in compliance with the national regulation (threshold level of 0.08 ppm). Generally, the high concentrations of formaldehyde are attributed to the materials used for interior decoration, as well as the emission from the detergents and cleaning agents.

Total volatile organic compounds

The threshold value for total volatile organic compounds in the indoor environment in Portugal is 0.6 mg/m^3 (0.26 ppm, if referred to isobutylene; 0.16 ppm, when referred to toluene) (RSECE 2006). The maximum concentrations of TVOC were below the limit value at each building, except building "1" (office) which is mainly resulting from emissions by the consumer products used, the furnishing, and office equipment.

Ozone

In this study, the concentrations of ozone were below 0.07 mg/m^3, in accordance with the national IAQ regulation which mandates the O_3 concentration not to exceed 0.2 mg/m^3 (0.1 ppm) (RSECE 2006).

Biological indicators

The recommended threshold value for total concentration of bacteria and fungi in indoor air is 500 CFU/m^3 in Portugal. The results for this measurement (Table 1) indicate that the indoor air microbial pollution at each building are all below the limit values. In the present work, *Legionella* sp. was not detected in the buildings, except in the hotel where a high concentration (3,800 CFU/L) was found in the water sample from a shower of the staff locker room (at level −1). Although the pathogenic species was not present, a thermal decontamination of the whole HW ductwork of the hotel was immediately determined and implemented. Repeated water samplings just after the decontamination process and 2 weeks later allowed concluding that the problem had been solved. However, a more detailed search was conducted to find the reasons for that event and the conclusions pointed out several concomitant critical factors for bacterial contamination: (a) the showers of the staff locker rooms were seldom used and (b) they were the most distant from the HW tanks (on the roof). Furthermore, (c) the hot water supply from the HW recirculation circuit to these spaces was made by a 20-m section of pipe that was found to be degraded (internal oxidation noticeable by the color of the sampling water). This section of degraded pipe provided a volume of stagnant warm water, thus meeting all the conditions for the bacterial proliferation. Renovation of this section of pipe and the planning of monthly disinfection of all shower terminals were the practical results as dictated in the respective IAQ audit report. A fourth critical factor was (d) the insufficiently high storage temperature in the hot water tanks (56°C), which was attributed to technical difficulties that were further identified in the simultaneous energy audit (global inspection of the HVAC systems) and related with the inadequate installation of the plate heat exchanger for HW production, that was found to be operating in co-current mode. The correction of the heat exchanger connections was a simple corrective action that effectively solved the referred technical limitations.

Discussion

An assessment of indoor air quality in four public buildings in Portugal was conducted. The results of these IAQ audits show that most of the measured indicators are within the threshold limits, although some problems or situations with risk for the good IAQ in some buildings were identified, such as: (1) excessive CO_2 concentration in hotel and school buildings during the period of occupancy (insufficient ventilation); (2) too high particle concentrations; (3) lack of regular hygiene and maintenance of HVAC systems; (4) poor filtration effectiveness in all AHUs; and (5) bacterial contamination of the hot water ductwork (hotel).

These findings led to a set of recommendations for improvement of IAQ conditions in buildings, namely:

1. Improve the methodologies and increase the frequency of indoor cleaning
2. Regular cleaning of all AHUs and its components
3. Replacement (hotel) and refurbishment of AHUs, to install a prefilter and more efficient final filters
4. Provision of higher fresh air ratios or increase of ventilation rate during occupancy period
5. Absolutely forbid smoking indoors (office building)
6. Replacement of degraded and critical section of hot water piping
7. Correction of HW heat exchanger installation and set a minimum of 60°C for HW storage temperature

In addition to the above common recommendations, some specific guidelines were also suggested to the facility managers according to each building-specific IAQ situation. Finally, the building managers were sensitized for the importance of guaranteeing good IAQ in the buildings.

Conclusion

Indoor air quality assessment of buildings is a process that includes different types of procedures. A qualified building survey, correct sampling procedures, and a good evaluation and analysis of the information that is gathered from sampling procedures is crucial in order to obtain a satisfactory result. It is important for the investigator to be able to evaluate the results from measurements and correlate them with in situ observations, in order to create hypotheses regarding possible causes for the IAQ problems to be solved and/or actions to be taken. The financial budget in most building IAQ evaluation is limited. This makes it important that the periodic IAQ assessment method can be performed in a practical manner and representative enough without being expensive.

This study presented practical information and guidelines on how to establish and conduct the comprehensive IAQ audit approach for public buildings, based on Portugal national laws and previous experience of the authors. The procedure presented for IAQ audit of public buildings proved to be simple and comprehensive. The conclusion is that such a methodology is suitable for short-period assessment on public buildings, being useful for finding the appropriate remediation actions to solve the IAQ problems in such buildings.

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APPENDIX E PAPER PUBLISHED AT ENERGY AND BUILDINGS JOURNAL: MULTI-OBJECTIVE OPTIMIZATION FOR BUILDING RETROFIT STRATEGIES: A MODEL AND AN APPLICATION

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Multi-objective optimization for building retrofit strategies: A model and an application

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ABSTRACT

Due to growing limitations on land use and awareness of sustainability concerns, the building retrofit market has faced increasing opportunities worldwide. Several technological/constructive options are available to improve energy efficiency and indoor environmental quality in buildings. The identification of the most appropriate retrofitting options is a topic of outstanding importance given the potential costs and impacts involved.

This paper presents a multi-objective optimization model to assist stakeholders in the definition of intervention measures aimed at minimizing the energy use in the building in a cost effective manner, while satisfying the occupant needs and requirements. An existing house needing refurbishment is taken as a case study to demonstrate the feasibility of the proposed multi-objective model in a real-world situation. The results corroborate the practicability of this approach and highlight potential problems that may arise.

1. Introduction

The building sector is the largest user of energy and CO_2 emitter in the European Union (EU) and is responsible for about 40% of the EU's total final energy consumption and CO_2 emissions. Even if all future buildings were to be built so that their energy demands were very low, this would still only means that the increase in energy demands would be reduced and it would not reduce the present demands. For many years to come, only measures taken in existing buildings will have a significant effect on the total energy demands in the building stock. As a consequence, the cornerstone of the European energy policy has an explicit orientation to the conservation and rational use of energy in buildings as the energy performance of building directive (EPBD) 2002/91/EC and its recast (EPBD) 2010/31/EU indicate [1,2]. The EPBD's main objective is to promote the cost-effective improvement of the overall energy performance of buildings. One of the best opportunities to do so would be during building retrofit. Although a thorough building's retrofit evaluation is quite difficult to undertake, because a building and its environment are complex systems (since economical, technical, technological, ecological, social, comfort, and esthetical aspects, among others must be taken into account), in which all sub-systems influence the overall efficiency performance and the interdependence between sub-systems plays a significant role [3].

Furthermore, as innovative technologies and energy efficiency measures for buildings are well known, the main issue is to identify those that will prove to be the more effective and reliable in the long term. When choosing among a variety of proposed measures, the Decision Maker (DM) (the corresponding building expert) has to reconcile environmental, energy related, financial, legal regulation and social factors to reach the best possible compromise to satisfy the final occupant needs and requirements.

Several decision aid approaches (cost-benefit analysis [4], multi-criteria analysis [5–11], multi-objective optimization [12,13], energy rating systems [14,15], etc.) have been used for addressing the mentioned and other related problems.

Goodacre et al. [4] used a cost-benefit analysis framework to assess the potential scale of some of the benefits from upgrading heating and hot water energy efficiency in the English building stock.

Gero et al. [5] were among the first to propose a multi-criteria (MC) model to be used at the process of building design in order to explore the trade-offs between the building thermal

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performance and other criteria such as capital cost and usable area of the building. More recently, other researchers have also employed MC techniques to similar problems. Jaggs and Palmar [6], Flourentzou and Roulet [7], and Rey [8] proposed MC-based approaches for the evaluation of retrofitting scenarios. Blondeau et al. [7] used MC analysis to determine the most suitable ventilation strategy in a university building among a set of actions. Their aim was to ensure the best possible indoor air quality and thermal comfort of the occupants and the lowest energy consumption. Kaklauskas et al. [3] developed a multivariate design method and MC analysis for building refurbishment, by determining the significance, priorities and utility degree of building refurbishment alternatives and selecting the most recommended variant. Allane [10] used a MC knapsack model to select the most feasible actions in the conceptual phase of a renovation project. Kim et al. [11] developed a genetic algorithm-based decision support system for housing condition assessment that suggests optimal refurbishment actions considering the trade-off between cost and quality. Diakaki et al. [12] investigated the feasibility of applying multi-objective optimization techniques to the problem of improving energy efficiency in buildings.

These lines of research have allowed addressing many problems as far as buildings retrofit is concerned. However, most of them consider that a list of predefined and pre-evaluated intervention options/solutions is given. In case a small number of such solutions have been defined, there is no guarantee that the solution finally reached is the best one (from the DM's perspective). On the opposite, when a large number of solutions is defined the required evaluation and selection process may become extremely difficult to handle.

The problem faced by the DM is in fact a multi-objective optimization problem, characterized by the existence of multiple and competing objectives for assessing the merits of the potential solutions according to different evaluation axes, a set of feasible solutions that are not predefined but are implicitly defined by a set of parameters and constraints that should be taken into account to reach the best possible solution [12]. Accordingly, this paper presents a multi-objective optimization model to quantitatively assess technology choices in a building retrofit project. This model takes into account all feasible combinations of choices (concerning windows, insulation materials for roofs and walls, and solar collectors), without being confined to a small set of predefined scenarios in building retrofit. To this end, an illustrative real residential building is used to demonstrate the feasibility of the proposed approach and highlight potential problem that may arise. The DM is provided solutions corresponding to different trade-offs between energy savings and retrofit costs. A solution to obtain a desired efficiency label at minimum cost can also be identified.

The remainder of this paper is organized as follows. The proposed multi-objective optimization model is presented in the next section. It is followed by the application of the proposed model to a real-world case study. Finally Section 4 summarises conclusions and discusses issues for future works.

2. Theory and methodology

2.1. Multi-objective optimization problem

This study considers the multi-objective optimization (MOO) of buildings retrofit strategies. Therefore, it requires the definition of appropriate decision variables, objective functions and constraints, and finally the selection of appropriate solution techniques. The decision variables reflect the whole set of alternative measures that are available for the retrofitting of the building (e.g. windows, insulation material, etc.). The objectives to be achieved (minimum retrofit cost and maximum energy savings) are defined using the appropriate linear or non-linear mathematical formulations. Moreover, the set of feasible solutions is delimitated with respect to logical, physical and technical constraints concerning the decision variables and their intermediary relations.

2.2. Decision variables

The set of retrofit actions in this study concerns combinations of choices regarding windows, external wall insulation material, roof insulation material, and installation of solar collector to the existing building. Therefore, four types of decision variables are defined concerning the alternative choices regarding:

- the windows type;
- the external wall insulation materials;
- the roof insulation materials;
- the solar collector type.

For simplicity, it is assumed that only one retrofit action from each four set of actions may be selected for the building retrofit.

Assuming availability of I alternative types of windows, J alternative types of external wall insulation material, K alternative types of roof insulation material, and L alternative types of solar collector, binary variables x_i^{WIN} with $i=1,\ldots,I$, x_j^{EWAL} with $j=1,\ldots,J$, x_k^{ROF} with $k=1,\ldots,K$, and x_l^{SC} with $l=1,\ldots,L$ are defined as follows:

$$x_i^{WIN}=\begin{cases}1, & \text{if window type } i \text{ is selected}\\ 0, & \text{otherwise}\end{cases} \quad (2.1)$$

$$x_j^{EWAL}=\begin{cases}1, & \text{if insulation material type } j \text{ is selected otherwise}\\ 0, & \text{otherwise}\end{cases} \quad (2.2)$$

$$x_k^{ROF}=\begin{cases}1, & \text{insulation material type } k \text{ is selected otherwise}\\ 0, & \text{otherwise}\end{cases} \quad (2.3)$$

$$x_l^{SC}=\begin{cases}1, & \text{if solar collector type } l \text{ is selected}\\ 0, & \text{otherwise}\end{cases} \quad (2.4)$$

2.3. Objective function calculation procedures

2.3.1. Energy savings

The general procedure for estimating the energy savings, ES, from a retrofit project is based on the calculation of the difference between the pre-retrofit energy consumption predicted from a model and the post-retrofit energy consumption [15]:

$$ES=E_{pre}-E_{post} \quad (2.5)$$

where

- E_{pre} – the energy use predicted from a pre-retrofit model of the facility.
- E_{post} – the energy used in the facility after implementing the retrofit actions predicted from a model.

Therefore, it is important to develop a model for the building before estimating the retrofit energy savings. To limit the computational time, a simple thermal model of the building is developed based on the current methodology of the Portuguese building thermal code (RCCTE) [16], which is based on ISO-13790 [17].

Generally the energy sources in a building are used for space heating, cooling and domestic hot water (DHW) systems and for electric lighting (in this specific model electric lighting is not considered). The building energy needs ($E=E_{pre}$ or E_{post}) are calculated using Eq. (2.6):

$$E=Q_{hc}+Q_{cc}+Q_{ac} \quad (2.6)$$

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where

- Q_{ic} – energy needed for space heating [kWh/year];
- Q_{vc} – energy needed for space cooling [kWh/year];
- Q_{ac} – energy needed for water heating [kWh/year].

A steady-state yearly based calculation methodology is used here to estimate the heating and cooling needs of residential buildings, as well as the DHW needs. The heating needs are obtained applying a degree-days method and the envelope heat balance for the heating season. The cooling needs are obtained from the average difference between the indoor–outdoor temperature and the envelope heat balance during the cooling period. The DHW needs are obtained applying the average daily reference consumption and the annual number of days of DHW consumption.

2.3.1.1. Energy need for heating. For each building zone and each season, the building energy need for space heating, $Q_{ic}(x)$ (x denotes the vector of all decision variables defined in Section 2.2), for conditions of continuous heating, is calculated as given by Eqs. (2.7)–(2.14):

$$Q_{ic}(x) = Q_t(x) + Q_v - Q_{gu}(x) \text{ [kWh/year]} \quad (2.7)$$

$$Q_t(x) = Q_{ext}(x) + Q_{enu} - Q_{pt} \text{ [kWh/year]} \quad (2.8)$$

$$Q_{ext}(x) = 0.024 \cdot DD \cdot BLC_{ext} \text{ [kWh/year]} \quad (2.9)$$

$$BLC_{ext} = A_{win}\sum_{i=1}^{I} U_i \cdot x_i^{win} + \frac{A_{EWAL}}{\sum_{j=1}^{J} x_j^{EWAL} d_j/\lambda_j} + \frac{A_{ROF}}{\sum_{k=1}^{K} x_k^{ROF} d_k/\lambda_k} \quad (2.10)$$

$$Q_{enu} = 0.024 \cdot DD \cdot U \cdot A2 \text{ [kWh/year]} \quad (2.11)$$

$$Q_{pt} = 0.024 \cdot DD \cdot \sum\nolimits_m \Psi_m \cdot B_m \text{ [kWh/year]} \quad (2.12)$$

$$Q_v = 0.024 \cdot (0.34 \cdot ACH \cdot A_p \cdot P_d) \cdot DD \text{ [kWh/year]} \quad (2.13)$$

$$Q_{gu}(x) = \eta[(0.720 \cdot A_p \cdot M \cdot q_i) + (M \cdot G_{south} \cdot \sum\nolimits_i X_i \cdot A_{e,i} \cdot x_i^{win})] \text{ [kWh/year]} \quad (2.14)$$

where
Coefficients:

- τ – losses to non-heated spaces reduction coefficient [kWh/year];
- Ψ – linear heat flux transmission coefficient [W/m °C];
- X_i – orientation coefficient for the different facade orientations;

Parameters:

- U_i – window type i thermal transmission coefficient [W/m² °C];
- A_{win} – windows surface area [m²];
- λ_j – thermal conductivity of external wall insulation material [W/m °C];
- d_j – thickness of the external wall insulation [m];
- A_{EWAL} – exterior wall surface area [m²];
- λ_k – thermal conductivity of the roof insulation material [W/m °C];
- d_k – thickness of the roof insulation [m];
- A_{ROF} – roof surface area [m²];
- ACH – air changes per hour [h⁻¹];
- DD – Degree-Days [°C/day];
- q_i – internal gains [W/m²];
- M – heating season duration [months];
- G_{south} – average monthly solar energy that reaches a south oriented vertical surface [kWh/m² month];
- η – heat gains utilization factor;
- $Q_t(x)$ – conduction heat loss through building envelope [kWh/year];
- Q_v – heat loss due to fresh air flow [kWh/year];
- $Q_{gu}(x)$ – useful heat gains (internal + solar heat gains through glazing) [kWh/year];
- $Q_{ext}(x)$ – heat loss through zones in contact with outdoor (walls, glazing, roofs and pavements) [kWh/year];
- $Q_{enu}(x)$ – heat loss through zones in contact with non-useful spaces (walls, glazing, roofs and pavements) [kWh/year];
- $Q_{pt}(x)$ – heat loss through linear thermal bridges [kWh/year];
- BLC_{ext} – building load coefficient [W/°C];
- $A2$ – building envelope in contact with non-heated spaces [m²];
- B – floor or wall interior linear perimeter for envelope in contact with the soil or thermal bridge interior length [m];
- A_p – net floor area [m²];
- P_d – floor to ceiling height [m];
- A_e – effective glazing solar radiation collector area for the different windows orientations.

2.3.1.2. Energy need for cooling. The cooling needs are obtained applying the following equation:

$$Q_{vc}(x) = (1 - \eta) \cdot (Q_1(x) + Q_{gu}(x) + Q_2 + Q_3) \text{ [kWh/year]} \quad (2.15)$$

$$Q_1(x) = 2.928 \cdot BLC_{ext} \cdot (\theta_m - 25) + BLC_{ext} \cdot [(\alpha \cdot Ir/25)] \text{ [kWh/year]} \quad (2.16)$$

$$Q_2(x) = 2.928 \cdot (0.34 \cdot ACH \cdot A_p \cdot P_d)(\theta_m - 25) \text{ [kWh/year]} \quad (2.17)$$

$$Q_3 = 2.928 \cdot A_p \cdot q_i \text{ [kWh/year]} \quad (2.18)$$

where

- θ_m – average outdoor temperature in the cooling season;
- α – exterior envelope solar radiation absorption coefficient;
- Ir – solar radiation intensity for each orientation [W/m²];
- Q_1 – heat gain through envelope [kWh/year];
- Q_2[1] – heat transfer due to infiltration [kWh/year];
- Q_3 – internal heat gains [kWh/year].

2.3.1.3. Energy needs for water heating. The DHW needs are obtained applying the following equations:

$$Q_{ac}(x) = \left(\frac{Q_a}{\eta} - E_{solar}(x) - E_{ren}\right) \text{ [kWh/year]} \quad (2.19)$$

$$Q_a = 0.081 \cdot M_{AQS} \cdot n_d \text{ [kWh/year]} \quad (2.20)$$

$$E_{solar}(x) = \sum_{l}^{L} E_l^{sol} \cdot x_l^{sc} \text{ [kWh/year]} \quad (2.21)$$

where
Coefficient:

- η_a – DHW system efficiency;

Parameters:

[1] This term is a negative heat gain, as the average outdoor temperature is always less than indoor air set-point temperature in cooling season (Annex III, RCCTE).

- M_{AQS} – average daily reference consumption;
- n_d – annual number of days with DHW consumption;
- $E_l^{sol}(x)$ – energy contribution from solar collector type l;
- E_{ren} – energy contribution from other renewable sources;
- Q_a – energy supplied with conventional systems for DHW [kWh/year].

2.3.2. Retrofit cost

The overall investment cost for the retrofit of the building is calculated by adding the retrofit costs corresponding to each action as follows:

$$ReCost(x) = A_{win}\sum_{i=1}^{I} C_i^{WIN} \cdot x_i^{win} + A_{EWAL}\sum_{j=1}^{J} C_j^{EWAL} \cdot x_j^{EWAL} + A_{EWAL}\sum_{k=1}^{K} C_k^{ROF} \cdot x_k^{ROF} + \sum_{l=1}^{L} C_l^{SC} \cdot x_l^{SC} \quad (2.22)$$

where

- C_i^{WIN} – cost in [€/m²] for window type *i*;
- C_j^{EWAL} – cost in [€/m²] for external wall insulation material type *j*;
- C_k^{ROF} – cost in [€/m²] for roof insulation material type *k*;
- C_l^{SC} – cost for solar collector type *l*.

2.4. Solution techniques

The decision variables, objective functions and constraints developed above, lead to the formulation of the multi-objective programming problem:

$$\begin{aligned} &Min Z_1(x) = ReCost(x) \\ &Max Z_2(x) = ES(x) \\ &S.t. \\ &x_i^{win} \in \{0,1\} \ \forall i \in \{1,2,\ldots,I\} \\ &x_j^{EWAL} \in \{0,1\} \ \forall j \in \{1,2,\ldots,J\} \\ &x_k^{ROF} \in \{0,1\} \ \forall k \in \{1,2,\ldots,K\} \\ &x_l^{sc} \in \{0,1\} \ \forall l \in \{1,2,\ldots,L\} \\ &\sum_{i=1}^{I} x_i^{win} = 1 \\ &\sum_{j=1}^{J} x_j^{EWAL} = 1 \\ &\sum_{k=1}^{K} x_K^{ROF} = 1 \\ &\sum_{l=1}^{L} x_l^{sc} = 1 \end{aligned} \quad (2.23)$$

Problem (2.23) is a combinatorial bi-objective problem, in which the objective functions cost and energy savings are conflicting.

The model has been implemented in MATLAB [18] and a Tchebycheff programming technique has been developed to tackle the multi-objective optimization.

To apply Tchebycheff programming, the decision model is rearranged to aggregate the two objective functions. In this method weighting vectors λ are used to define different weighted Tchebycheff metrics [19]. As a first step, the ideal objective function vector Z^* should be computed.

$$\begin{aligned} &Z_i^* = \max(Z_i(x)|x \in S) \quad \text{if } Z_i \text{ to be maximized} \\ &Z_i^* = \min(Z_i(x)|x \in S) \quad \text{if } Z_i \text{ to be minimized} \end{aligned} \quad (2.24)$$

The problem is then formulated in a way to compute the solutions closest to Z^*, according to those metrics. Therefore, the problem is formulated as follows:

$$\begin{aligned} &Min(\alpha) \\ &s.t. \\ &\alpha \ge (Z_1(x) - Z_1^*)\left(\frac{\lambda_1}{Z_1^*}\right) \\ &\alpha \ge (Z_2^* - Z_2(x))\left(\frac{\lambda_2}{Z_2^*}\right) \\ &\alpha \ge 0 \\ &x_i^{win} \in \{0,1\} \ \forall i \in \{1,2,\ldots,I\} \\ &x_j^{EWAL} \in \{0,1\} \ \forall j \in \{1,2,\ldots,J\} \\ &x_k^{ROF} \in \{0,1\} \ \forall k \in \{1,2,\ldots,K\} \\ &x_l^{sc} \in \{0,1\} \ \forall l \in \{1,2,\ldots,L\} \\ &\sum_{i=1}^{I} x_i^{win} = 1 \\ &\sum_{j=1}^{J} x_j^{EWAL} = 1 \\ &\sum_{k=1}^{K} x_K^{ROF} = 1 \\ &\sum_{l=1}^{L} x_l^{sc} = 1 \end{aligned} \quad (2.25)$$

In this formulation, λ_1 and λ_2 are two constants representing the weight of each objective. These weights can be changed to obtain different compromise solutions. For strictly positive weight values this formulation yields solutions that are non-dominated (efficient, Pareto optimal); for each of these solutions there is no other solution able to improve one of the objectives without worsening the other objective.

3. An illustrative example

This section is aimed at illustrating how the approach described in Section 2 can be used to provide decision support for selecting a satisfactory compromise solution based on the MOO model. The building under study is a semi-detached house (one family) constructed in 1945, situated in central region of Portugal (Fig. 1). The number of degree-days, heating season duration, the average temperatures and the corresponding solar radiations have been extracted from the national regulation (RCCTE). The building has a ground floor and a basement. The two stories are connected by a staircase (Fig. 1). The gross floor area of the house is 97 m² and its average height is 2.47 m. The glazing area represents 10% of the floor area.

The building has a concrete structure. The walls are built in concrete with no thermal insulation (U = 2.37 W/m² K). The house has standard single glazing (U = 3.4 W/m² K) and window frames are in wood. Its main facade is toward south-east. The house is heated with electrical heaters, using a natural gas standard boiler for both space heating and sanitary hot water production.

According to the Portuguese regulations, internal temperatures for heating and cooling periods have been set to θ_H = 20 °C and θ_{IC} = 25 °C, respectively. Temperature for heating water has been set to 45 °C. In addition, the internal heat gain per unit of floor area is set to 4 (W/m²).

For heating, cooling and hot water supply, electricity is taken into account as the main source, while solar energy is only considered for hot water supply.

After introducing the required data into an excel spreadsheet, the program developed imports the data into MATLAB

APPENDIX E PAPER PUBLISHED AT ENERGY AND BUILDINGS JOURNAL: MULTI-OBJECTIVE OPTIMIZATION FOR BUILDING RETROFIT STRATEGIES: A MODEL AND AN APPLICATION

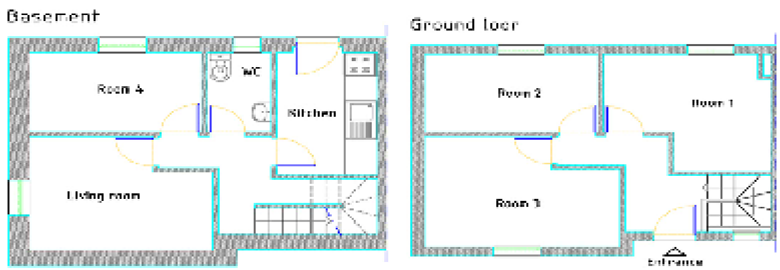

Fig. 1. Schematic plan of basement and ground floor of case study.

Table 1
Building energy analysis before retrofit.

Building performance indicators	
Estimated global annual primary energy for heating, cooling and water heating	12.80 [kgoe/m^2 year]
Existing building total energy consumption	31641.58 [kWh/year]
Existing building Energetic Classification	C
Existing building CO_2 emission	1.4945 [TCO_2/year]

automatically for further analysis, including prediction of the building energy use before retrofit.

The summary of results from the energy analysis of the building before retrofit is reported in Table 1.

A list of alternative retrofit actions applied in this study is based on a CYPE rehabilitation price generator database [20] extracted by the authors. Typical retrofit actions including different window types, external wall insulation materials, roof insulation materials, and solar collectors have been introduced on the list aiming at improving the building energy saving by decreasing energy consumption and retrofit cost. Tables 2–5 present the retrofit actions that will be referred to in the results (these are a subset of the 101 retrofit actions considered).

After the energy analysis of the building, the non-dominated solutions to the MOO problem that individually optimize each objective function are computed (solutions S1 and S2 in Table 6) using the function *bintprog* in MATLAB's optimization toolbox. The components of the ideal solution, which is the initial reference point, are displayed in bold italic. Table 6 also indicates the row numbers of corresponding retrofit actions leading to the S1 and S2

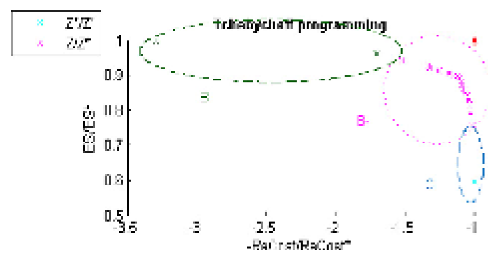

Fig. 2. Normalized multi objective solutions for the building retrofit strategies.

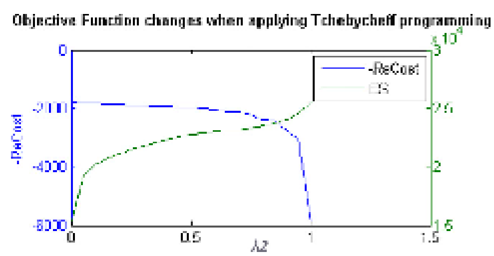

Fig. 3. Objective functions change when the corresponding weights in the Thebycheff formulation change.

Table 2
Characteristics of alternative windows.

N	Type	Thermal transmittance (W/m^2·C)	Effective solar energy transmittance (%)	Cost (€/m^2)
1	Single glazing Typical glazing	5.10	85.00	34.08
2	2bl glazing Without thermal break Uncoated air-filled metallic frame 4-12-4	2.80	75.00	39.42
3	2bl glazing Without thermal break Uncoated air-filled metallic frame 4-16-4	2.70	75.00	40.31
4	2bl glazing Low-e window (with thermal break) coated air-filled metallic frame 4-12-4 NEUTRALUX	1.60	62.00	55.72
5	2bl glazing Window air-filled metallic frame 6-12-4 SOLARLUX Supernatural 70/40 Temprado	1.60	44.00	135.53

Table 3
Characteristics of alternative external wall insulation materials.

N	Insulation types	Thickness (m)	Thermal conductivity (W/m °C)	Cost (€/m²)
1	Stone wool	0.03	0.034	11.25
2	Glass wool	0.05	0.038	12.67
3	EPS (expanded polystyren)	0.03	0.036	7.64
4		0.07	0.036	10.44
5		0.08	0.036	11.15
6		0.08	0.033	16.38
7		0.04	0.036	8.1
8		0.06	0.036	9.56
9	Sprayed polyurethane	0.02	0.042	6.39
10	Cork	0.01	0.04	3.05
11		0.10	0.04	17.95
12		0.15	0.04	26.93
13		0.30	0.04	53.85

Table 4
Characteristics of alternative roof insulation materials.

N	Insulation types	Thickness (m)	Thermal conductivity (W/m °C)	Cost (€/m²)
1	Sprayed polyurethane	0.02	0.042	6.39
2	EPS (expanded polystyren)	0.03	0.033	4.32
3		0.04	0.033	5.6
4		0.05	0.033	6.87
5		0.06	0.033	8.14
6		0.07	0.033	9.43
7		0.08	0.033	10.7
8	XPS (extruded polystyren)	0.04	0.034	11.64
9	Stone wool	0.065	0.037	24.67
10		0.105	0.037	34.8

solutions, as well as the building energy classification after implementing the associated retrofit action package.

The non-dominated solution that minimizes the Tchebycheff distance (that is, minimizes the largest deviation) to the ideal solution is then computed for different combinations of objective function weight coefficients using a modified version of the *bintprog* function in MATLAB, which makes the construction of the non-dominated frontier possible. Table 7 shows the objective function values at an equally spaced finite number of λ values. As the weight

Table 5
Characteristics of alternative solar collector systems.

N	Type	E.Solar (kWh)	Cost (€/m²)
1	AZIMUT145P1 (1plain collector with Thermosyphon)	1061	1645.1
2	AZIMUT192P2 (2plain collector with Thermosyphon)	1865	2402.27
3	JUNKERS (1plain collector with Thermosyphon) A1/TS150/FKB	1048	1900.9
4	DANOSA SOLAR TDS150/CIS (1plain collector with Thermosyphon)	1048	1465.47
5	DANOSA SOLAR TDS200/CIS (2plain collector with Thermosyphon)	1900	2113.5
6	JUNKERS (2plain collector with Thermosyphon) A1/TS150/FKB Inclination39	1920	3135.54

Note: E.Solar (kWh) that is the energy production from solar collector has been calculated by SOLTERM software [21] which is developed by the Portuguese National Laboratory for Energy and Geology (LNEG).

coefficient of the energy saving objective increases, the solution to problem (2,25) approaches the optimum solution when only the second objective is optimized and finally reaches it (when $\lambda_1 = 0$, $\lambda_2 = 1$). As the weight coefficient of the retrofit cost objective function increases, the solution approaches the optimum solution when the first objective is optimized individually. The values in Table 7 were used to construct the graph shown in Fig. 2, displaying some of the points that lie on the non-dominated solution frontier. Choosing each solution from this frontier will lead to different retrofit cost/energy saving trade-offs, possibly leading to distinct energy classification of the building according to Portuguese code (RCCTE). The location of the ideal solution is also shown (red star). In terms of retrofit actions, we can note that in the right hand side of the curve a small increase of retrofit cost can lead to an improvement of the energy classification of the building from C to B⁻. In the left hand side, the situation is more difficult, and a large amount of investment is required to improve the energy classification of the building from B⁻ to B. This case highlights the major advantage of a multi-objective formulation, which is to provide a thorough understanding of the trade-offs between the competing objectives, and bring the potentiality of each investment into focus. In the current case the building owner could be easily convinced to slightly increase the amount of investment from €1791 to €1814 in order to improve energy classification of the building by one level.

Table 6
Non-dominated solutions.

Solution	*ReCost* (€)	*ES* (kWh/year)	Window type	*EWAL* insulation	*ROF* insulation	Solar collector	Energy classification
S1	*1791*	15263	1	10	1	4	C
S2	5901	*25539*	4	13	10	6	B

Table 7
Problem solution applying Tchebycheff programming.

Z	λ_1	λ_2	*ReCost* (€)	*ES* (kWh/year)	Window type	*EWAL* insulation	*ROF* insulation	Solar collector	Energy classification
0.00	1.00	0.00	1791.12	15263.06	1	10	1	4	C
0.02	0.90	0.10	1834.12	20229.46	1	7	3	4	B⁻
0.03	0.80	0.20	1865.05	21165.40	1	8	3	4	B⁻
0.04	0.70	0.30	1902.73	21765.78	1	4	5	4	B⁻
0.05	0.60	0.40	1941.81	22306.88	2	4	4	4	B⁻
0.05	0.50	0.50	1983.58	22769.88	2	5	6	4	B⁻
0.06	0.40	0.60	2057.09	23025.45	3	6	7	4	B⁻
0.07	0.30	0.70	2117.15	23158.30	3	11	7	4	B⁻
0.06	0.20	0.80	2361.89	23511.42	2	12	5	4	B⁻
0.05	0.10	0.90	2729.42	24047.54	4	12	10	4	B⁻
0.00	0.00	1.00	5901.16	25539.47	4	13	10	6	B

Fig. 3 demonstrates how the objective values change in relation with the specific value of the weights. This figure clearly shows the competitive nature of objective functions. As the weight on energy saving (λ_2) increases, the set of actions leading to higher energy savings and at the same time higher cost have been selected.

4. Conclusions and future work

Technological advances and new construction methods and techniques mean that in the very near future all new buildings can be nearly zero energy buildings. The big challenge is therefore existing buildings as these represent such a high proportion of world energy consumption and they will be with us for many decades to come. One of the best opportunities to improve energy efficiency of the buildings would be during building retrofit. One of the key steps in building retrofit is the selection of retrofit actions among a large number of possibilities. The problem is in fact a multi-objective optimization problem, characterized by the existence of multiple and competing objectives, a set of feasible solutions that are not predefined but are implicitly defined by a set of parameters and a set of constraints that should be taken into account to reach the best possible solution. However, the problem is usually approached through simulation that focuses on particular aspects of the problem rather than a global confrontation. Accordingly, the aim of this paper was to develop a multi-objective mathematical model to provide decision support in the evaluation of technology choices for the building retrofit strategies. The model allows explicitly for the simultaneous consideration of all available combinations of alternative retrofit actions. It also allows for the consideration of logical, physical and technical constraints. The result of the application of a Tchebycheff programming technique to compute solutions to the model shows the feasibility of this methodology to find well balanced strategies for retrofitting of buildings to be presented to a DM in the framework of a decision support process.

As stated earlier, to limit the computational time, a simple thermal model of the building has been developed based on the current methodology of the Portuguese building thermal code (RCCTE). It would be interesting to include more objective functions related to the building behaviour such as an indoor thermal comfort or indoor air quality [22] that need a monthly or even hourly simulation. Unfortunately, this model is not able to perform such a detailed analysis of buildings. Therefore it remains to incorporate in the future more detailed thermal simulation such as an equivalent resistance–capacitance (R–C) model, which uses an hourly time step. The mentioned model makes a distinction between the internal air temperature and mean temperature of the internal surfaces (mean radiant temperature) that enables its use for thermal comfort considerations and increases the accuracy of building thermal model.

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APPENDIX F PAPER PUBLISHED AT BUILDING AND ENVIRONMENT JOURNAL: A MULTI-OBJECTIVE OPTIMIZATION MODEL FOR BUILDING RETROFIT STRATEGIES USING TRNSYS SIMULATIONS, GENOPT AND MATLA

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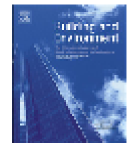

A multi-objective optimization model for building retrofit strategies using TRNSYS simulations, GenOpt and MATLAB

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ABSTRACT

Promoting the cost effective improvement of the overall energy performance of buildings is among the main objectives of the Energy Performance of Buildings Directive (EPBD) of the European Union, being even emphasized in its recent recast. One of the best opportunities to achieve that aim is during building retrofit.

In face of the multiple choices for retrofitting a building, the main issue is to identify those that prove to be the more effective and reliable in the long term. In this work, a simulation-based multi-objective optimization scheme (a combination of TRNSYS, GenOpt and a Tchebycheff optimization technique developed in MATLAB) is employed to optimize the retrofit cost, energy savings and thermal comfort of a residential building. A wide decision space is considered, including alternative materials for the external walls insulation, roof insulation, different window types, and installation of a solar collector in the existing building. A real-world case study is used to demonstrate the functionality of the proposed approach. The results verify the practicability of the approach and highlight potential problems that may arise.

1. Introduction

Europe aims at making its existing building stock more energy-efficient as a part of its plan to a low carbon-energy economy. The main legislative instrument in the European Union (EU) for improving the energy performance of buildings is the European Directive 2002/91/EC (EPBD) [1] and its recast (Directive 2010/31/EU) [2]. The EPBD recast strengthens the energy performance requirements, clarifies and streamlines some of its provisions to reduce the large differences between Member States' practices. It prescribes an ambitious target that all new buildings must be nearly zero energy buildings by 31 December 2020, while Member States should set intermediate targets for 2015. However, even if all future buildings were to be built so that their energy demands were very low, this would still only mean that the increase in energy demand would be reduced and it would not reduce the present demand. Fortunately, according to the new EPBD recast [2], EU Members States should also take measures and set targets, to stimulate building retrofits into nearly zero energy buildings. However, a thorough building retrofit evaluation is quite difficult to undertake, because a building and its environment are a complex system in which all sub-systems influence the overall efficiency performance and the interdependence between sub-systems plays a significant role.

In face of a large set of choices for retrofitting a building, the main issue is to identify those that prove to be the most effective in the long term. When choosing among a variety of proposed measures, the Decision Maker (DM) (the building expert) has to reconcile environmental, energy, financial, legal regulation and social factors to reach the best possible compromise solution to satisfy the final occupant needs. In practice, seeking such a solution is mainly attempted via two main approaches [3].

In the first approach, an energy analysis of the building is carried out and several alternative scenarios predefined by a building expert are developed and evaluated mainly through simulation [4]. Although many sophisticated energy simulation programs (e.g., TRNSYS, Energy Plus) are valuable tools to study the impact of

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alternative scenarios on building performance, the iterative trial-and-error process of searching for the best retrofit action is time-consuming and ineffective due to the inherent difficulty in exploring a large decision space (due to its combinatorial nature).

The second approach includes decision aid techniques such as cost-benefit analysis [5], multi-criteria analysis [6–12], multi-objective optimization [13,14,17], energy rating systems [15], usually combined with simulation to assist reaching a final decision among a set of alternative actions predefined by the building expert.

Gero et al. [6] were among the first to propose a multi-criteria (MC) model to be used at the process of building design in order to explore the trade-offs between the building thermal performance and other criteria such as capital cost and usable area. More recently, other researchers have also employed multi-criteria techniques to similar problems. Jaggs and Palmar [7], Flourentzou and Roulet [8], and Rey [9] proposed MC-based approaches for the evaluation of retrofitting scenarios. Kaklauskas et al. [16] developed a multivariate design method and multi-criteria analysis for building retrofit, determining the significance, priorities and utility degree of building retrofit alternatives and selecting the most recommended variant. Allane [11] used a multi-criteria knapsack model to select the most feasible retrofit actions in the conceptual phase of a retrofit project. Kim et al. [12] developed a genetic algorithm-based decision support system for housing condition assessment that suggests optimal retrofit actions considering the trade-off between cost and quality.

These lines of research have allowed addressing many problems as far as buildings retrofit is concerned. However, the problem when using MC techniques is that they are applied upon a set of predefined and pre-evaluated alternative solutions [3]. In case a small number of such solutions have been defined, there is no guarantee that the solution finally reached is the best one (from the DM's perspective). On the opposite, when a large number of solutions are defined the required evaluation and selection process may become extremely difficult to handle.

The problem faced by the DM is in fact a multi-objective optimization problem, characterized by the existence of multiple and competing objectives, the decision space consisting in a set of feasible solutions that are not predefined but are implicitly defined by a set of parameters and constraints that should be taken into account [14]. Therefore, it is not necessary to enumerate the set of actions to be considered.

Diakaki et al. [3] investigated the feasibility of applying multi-objective optimization techniques to the problem of improving energy efficiency in buildings, considering a simplified model for building thermal simulation. Asadi et al. [17] proposed a multi-objective optimization model that supports the definition of retrofit actions aimed at minimizing energy use in a cost effective manner. However, the thermal model did not allow the evaluation of indoor air quality related objective functions.

In the current study a multi-objective optimization approach is used and combined with TRNSYS (an energy simulation program) and GenOpt (an optimization program). The combination of these tools is used for the optimization of retrofit cost, energy savings and thermal comfort of a residential building, in the framework of a multi-objective model. Decision variables represent a wide selection of alternative materials for the external walls insulation, roof insulation, different window types, and installation of a solar collector to the existing building that are prescribed by a set of parameters and constraints. A case study is used to demonstrate the functionality of the proposed approach in a real-world setting.

The remainder of this paper is organized as follows. The problem formulation and the optimization approach are presented in the next section. The application to a real-world case is described in section 3. Finally, section 4 summarises conclusions and discusses issues for future consideration, research and development.

2. Multi-objective model and methodology

2.1. Optimization approach

In the current study, a simulation-based optimization scheme (Fig. 1) is developed to optimize multiple objective functions. The scheme is a combination of TRNSYS 16, GenOpt 3.0.3 and Optimizer under MATLAB environment. TRNSYS [18] is a transient system simulation program with a modular program structure that was designed to solve complex energy systems problems. The modular structure gives the program flexibility to be applied with different configurations in different settings. GenOpt is an optimization program for the minimization of a cost function that is evaluated by an external simulation program [19]. However, GenOpt is not capable of handling multi-objective optimization.

In this scheme a computer model of the building is first created in TRNSYS. The "Multi-zone Building" Type 56 is used to simulate the thermal behaviour of a building. Then it is necessary to obtain the results (including thermal loads, and Predicted Mean Vote (PMV) value) of implementing each retrofit action, regardless of the other actions. In order to automate TRNSYS runs, GenOpt is used. When associated with TRNSYS, GenOpt can automatically generate building (.bui) and deck (.dck) files, run TRNSYS with those files, save results, and restart again.

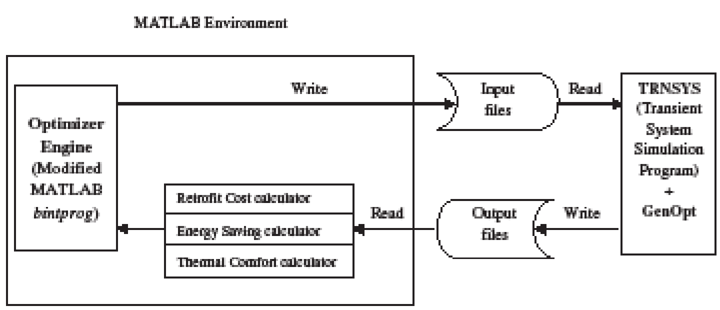

Fig. 1. Optimization framework.

Finally, an optimizer developed in MATLAB [20] is run to evaluate potential solutions. A Tchebycheff programming procedure has been developed in MATLAB to tackle the multi-objective optimization problem.

2.2. Formulation of the optimization problem

This study considers the multi-objective optimization (MOO) of buildings retrofit strategies. Therefore it requires the definition of appropriate decision variables, objective functions and constraints, and finally the selection of appropriate solution computation techniques.

2.2.1. Decision variables

The set of retrofit actions in this study concerns combinations of choices regarding external walls insulation material, roof insulation material, window types and installation of solar collector in the existing building. Therefore, four types of decision variables are defined concerning the alternative choices regarding:

- the external walls insulation materials;
- the roof insulation materials;
- the windows type;
- the solar collector type.

For simplicity, it is assumed that only one retrofit action from each four set of actions may be selected for the building retrofit. Nevertheless, this methodology can easily work with partitions of decision variables pertaining to the same type of characteristics (e.g., distinct external wall insulation materials for the North facade and the South facade).

Assuming the availability of I alternative types of external walls insulation material, J alternative types of roof insulation material, K alternative types of window, and L alternative types of solar collector, binary variables x_i^{EWAL} $(i = 1,\ldots,I)$, x_j^{ROF} $(j = 1,\ldots,J)$, x_k^{WIN} $(k = 1,\ldots,K)$, and x_l^{SC} $(l = 1,\ldots,L)$ are defined as follows:

$$x_i^{EWAL} = \begin{cases} 1, & \text{if insulation material type } i \text{ is selected} \\ 0, & \text{otherwise} \end{cases} \quad (2.1)$$

$$x_j^{ROF} = \begin{cases} 1, & \text{if insulation material type } j \text{ is selected} \\ 0, & \text{otherwise} \end{cases} \quad (2.2)$$

$$x_k^{WIN} = \begin{cases} 1, & \text{if window type } k \text{ is selected} \\ 0, & \text{otherwise} \end{cases} \quad (2.3)$$

$$x_l^{SC} = \begin{cases} 1, & \text{if solar collector type } l \text{ is selected} \\ 0, & \text{otherwise} \end{cases} \quad (2.4)$$

2.2.2. Objective functions

2.2.2.1. *Retrofit cost (ReCost).* The overall investment cost for the building retrofit ReCost(X) (X denotes the vector of all decision variables defined in Section 2.2.1) is calculated by adding individual retrofit action costs as follows:

$$\mathrm{ReCost}(X) = A_{EWAL}\sum_{i=1}^{I} C_i^{EWAL}\cdot x_i^{EWAL} + A_{ROF}\sum_{j=1}^{J} C_j^{ROF}\cdot x_j^{ROF} + A_{WIN}\sum_{k=1}^{K} C_k^{WIN}\cdot x_k^{WIN} + \sum_{l=1}^{L} C_l^{SC}\cdot x_l^{SC} \quad (2.5)$$

where:

- A_{EWAL} exterior wall surface area [m^2];
- C_i^{EWAL} cost in [€/m^2] for external wall insulation material type i;
- A_{ROF} roof surface area [m^2];
- C_j^{ROF} cost in [€/m^2] for roof insulation material type j;
- A_{WIN} windows surface area [m^2];
- C_k^{WIN} cost in [€/m^2] for window type k;
- C_l^{SC} cost for solar collector type l.

2.2.2.2. *Energy savings (ES).* The general procedure for estimating the energy savings, ES, from a retrofit project is based on the calculation of the difference between the pre-retrofit energy demand predicted from a model and the post-retrofit energy demand [4]:

$$\mathrm{ES}(X) = E_{pre} - E_{post}(X) \quad (2.6)$$

where

- E_{pre} the energy demand derived from a pre-retrofit simulation of the building.
- E_{post} the building energy demand after implementing the retrofit actions, predicted by simulation.

The annual energy demand of the building, calculated by TRNSYS, consists in energy demand for space heating, space cooling and domestic hot water (DHW) systems. Energy demand for lighting is not included because this is not expected to significantly change a result of the implementation of retrofit actions. Therefore, the building energy demands ($E = E_{Pre}$ and E_{Post}) are calculated using equation (2.7):

$$E = E_{heat} + E_{cool} + E_{DHW} \quad (2.7)$$

in which E_{heat} is the energy demand for space heating [kW h/year], E_{cool} is the energy demand for space cooling [kW h/year], and E_{DHW} is the energy demand for domestic hot water system [kW h/year].

The computation of E_{Post} is made using the individual effects computed for space heating, space cooling and domestic hot water (2.8–2.10).

$$E_{heat}(X) = \sum_{i=1}^{I} E_{heat,i}^{EWAL}\cdot x_i^{EWAL} + \sum_{j=1}^{J} E_{heat,j}^{ROF}\cdot x_j^{ROF} + \sum_{k=1}^{K} E_{heat,k}^{WIN}\cdot x_k^{WIN} \quad (2.8)$$

where, $E_{heat,i}^{EWAL}$ represents energy demand [kW h/year] for space heating after implementation of external wall insulation material type i, $E_{heat,j}^{ROF}$ represents energy demand [kW h/year] for space heating after implementation of roof insulation material type j and $E_{heat,k}^{WIN}$ represents energy demand [kW h/year] for space heating after implementation of window type k. All the mentioned energy demands are predicted by the simulation model.

$$E_{cool}(X) = \sum_{i=1}^{I} E_{cool,i}^{EWAL}\cdot x_i^{EWAL} + \sum_{j=1}^{J} E_{cool,j}^{ROF}\cdot x_j^{ROF} + \sum_{k=1}^{K} E_{cool,k}^{WIN}\cdot x_k^{WIN} \quad (2.9)$$

where, $E_{cool,i}^{EWAL}$ is energy demand [kW h/year] for space cooling after implementation of external wall insulation material type i, $E_{cool,j}^{ROF}$ is energy demand [kW h/year] for space cooling after implementation of roof insulation material type j and $E_{cool,k}^{WIN}$ [kW h/year] is energy demand for space cooling after implementation of window type k. All the mentioned energy demands are predicted by simulation model.

$$E_{DHW}(X) = \sum_{l=1}^{L} E_{DHW,l}^{SC} \cdot x_l^{SC} \quad (2.10)$$

where, $E_{DHW,l}^{SC}$ represents energy demand [kW h/year] for domestic hot water system after implementation of solar collector type l and is predicted by the simulation model.

2.2.2.3. *Thermal comfort (TPMVD).* The metric used to assess thermal comfort is the predicted mean vote (PMV), based on Fanger's model [21]. PMV is representative of what a large population would think of a thermal environment, and is used to assess thermal comfort in standards such as ISO 7730 [22] and ASHRAE 55 [23]. It ranges from −3 (too cold) to +3 (too warm), and a PMV value of zero is expected to provide the lowest percentage of dissatisfied people (PPD) among a population. In this study, an absolute value of 0.7 for PMV, the upper limit of the less exigent comfort category in ISO 7730, is considered as the borderline of the comfort zone. So, in order to maximize thermal comfort, the total percentage of cumulative time with discomfort ($|PMV| > 0.7$) over the whole year, that from now on will be mentioned as "percentage of discomfort hours (TPMVD(X))", should be minimized. The percentage of discomfort hours (TPMVD(X)) is also predicted by TRNSYS.

2.3. *Multi-objective optimization approach*

The decision variables, objective functions and constraints developed above, lead to the formulation of multi-objective programming problem (2.11):

$$\begin{aligned}
&\text{Min } Z_1(X) = \text{ReCost}(X)\\
&\text{Max } Z_2(X) = \text{ES}(X)\\
&\text{Min } Z_3(X) = \text{TPMVD}(X)\\
&\text{S.T.}\\
&x_i^{EWAL} \in \{0,1\} \;\; \forall \;\; i \in \{1,2,\ldots,I\}\\
&x_j^{ROF} \in \{0,1\} \;\; \forall \;\; j \in \{1,2,\ldots,J\}\\
&x_k^{WIN} \in \{0,1\} \;\; \forall \;\; k \in \{1,2,\ldots,K\}\\
&x_l^{SC} \in \{0,1\} \;\; \forall \;\; l \in \{1,2,\ldots,L\}\\
&\sum_{i=1}^{I} x_i^{EWAL} = 1\\
&\sum_{j=1}^{J} x_j^{ROF} = 1\\
&\sum_{k=1}^{K} x_k^{WIN} = 1\\
&\sum_{l=1}^{L} x_l^{SC} = 1
\end{aligned} \quad (2.11)$$

Problem (2.11) is a combinatorial multi-objective problem, in which the objective functions including retrofit cost, energy savings and percentage of discomfort hours are conflicting.

The model has been implemented in MATLAB [20] and a Tchebycheff programming procedure has been developed to tackle the multi-objective optimization.

To apply Tchebycheff programming, the decision model is rearranged to aggregate the three objective functions. In this method weighting vectors "p" are used to define different weighted Tchebycheff metrics [24]. As a first step, the ideal objective function vector Z^* should be computed, as follows ($i = 1, 2, 3$):

$$Z_i^* = \max\{Z_i(X) | X \in S\} \quad \text{if } Z_i \text{ to be maximized} \quad (2.12)$$

$$Z_i^* = \min\{Z_i(X) | X \in S\} \quad \text{if } Z_i \text{ to be minimized} \quad (2.13)$$

The problem is then formulated in a way to compute the solutions closest to Z^*, according to weighted metrics. The (weighted) Tchebycheff metric minimizes the largest (weighted) deviation to the ideal solution. Therefore, the problem for three objective functions is formulated as follows:

$$\begin{aligned}
&\text{Min}(\alpha)\\
&\text{S.T.}\\
&\alpha \ge \left(Z_1(X) - Z_1^*\right)\left(\frac{p_1}{Z_1^*}\right)\\
&\alpha \ge \left(Z_2^* - Z_2(X)\right)\left(\frac{p_2}{Z_2^*}\right)\\
&\alpha \ge \left(Z_3(X) - Z_3^*\right)\left(\frac{p_3}{Z_3^*}\right)\\
&\alpha \ge 0\\
&x_i^{EWAL} \in \{0,1\} \; \forall \; i \in \{1,2,\ldots,I\}\\
&x_j^{ROF} \in \{0,1\} \; \forall \; j \in \{1,2\ldots,J\}\\
&x_k^{WIN} \in \{0,1\} \; \forall \; k \in \{1,2,\ldots,K\}\\
&x_l^{SC} \in \{0,1\} \; \forall \; l \in \{1,2,\ldots,L\}\\
&\sum_{i=1}^{I} x_i^{EWAL} = 1\\
&\sum_{j=1}^{J} x_j^{ROF} = 1\\
&\sum_{k=1}^{K} x_k^{WIN} = 1\\
&\sum_{l=1}^{L} x_l^{SC} = 1
\end{aligned} \quad (2.14)$$

In this formulation, $((p_1, p_2, p_3) \in \overline{\Lambda}$ are constants representing the weight of each objective, where:

$$\overline{\Lambda} = \left\{ (p_1, p_2, p_3) \in R^3 \middle| p_i \ge 0, \sum_{i=1}^{3} p_i = 1 \right\}$$

For strictly positive weight values this formulation yields solutions that are non-dominated (efficient, Pareto optimal): for each of these solutions there is no other feasible solution able to improve one of the objectives without worsening, at least, one of the other objectives. These weights can be changed to obtain different compromise solutions. In this work weights have been used to sample the entire decision space and provide the DM a sub-set of non-dominated solutions that is representative of different trade-offs at stake in different regions of the decision space, thus avoiding an exhaustive computation. For this purpose, weights have been changed with a given step, while respecting $p_i \in \overline{\Lambda}$. The aim is to offer the DM usable information for actual decision purposes; for instance, grasping that in a certain region of the decision space it is necessary to sacrifice cost a significant amount to gain just a small amount in the energy savings objective function.

3. Example case study

3.1. *Building description*

The building studied is a semi-detached house (one family) constructed in 1945, situated in central region of Portugal (Fig. 2). The building has a ground floor and a basement. The two stories are connected by a staircase (Fig. 2). The gross floor area of the house is 97 m^2 and its average height is 2.47 m. The glazing area represents 10% of the floor area.

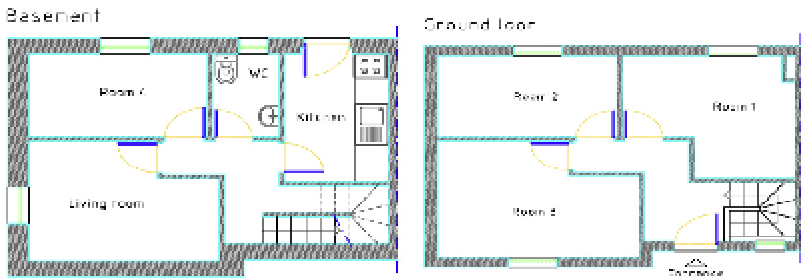

Fig. 2. Schematic plan of basement and ground floor of the case study.

The building has a concrete structure. The walls are built in concrete with no thermal insulation ($U = 2.37$ W/m^2 K). The house has standard single glazing ($U = 3.4$ W/m^2 K) and window frames are in wood. Its main facade is oriented towards south-east. The house is heated with electrical heaters, using also a standard natural gas boiler for both space heating and sanitary hot water production.

To reduce the execution time of simulation, a simplified model is used to represent the house as a single zone. A one year simulation was run in TRNSYS to determine the heating, cooling, domestic hot water (DHW) demands as well as PMV values. Type 109 and Type 56 were used for the weather condition and building definition in TRNSYS. Some of the parameters (besides the building characteristics mentioned above) introduced in Type 56 of TRNSYS were: 2 occupants with the activity level of 1 met (1 met = 58.15 W/m^2) in the room; total internal heat gain due to equipment and lighting equal to 4 W/m^2; infiltration rate of 0.9 air changes/hour.

In this work, PMV values are also calculated by TRNSYS, using a constant metabolic rate 1 met, a constant air velocity of 0.1 m/s, and a clothing factor equal to 0.5 clo in summer, 0.9 clo in winter, and 0.8 during the rest of the year. A summary of the results from the energy analysis of the building before retrofit is reported in Table 1.

A list of alternative retrofit actions applied in this study is based on a CYPE rehabilitation price generator database [25] extracted by the authors. Typical retrofit actions including different external wall insulation materials, roof insulation materials, window types and solar collectors have been introduced in the list aiming at improving the building energy savings and thermal comfort in a cost effective manner. Tables 2–5 present the characteristics of materials to be used in those retrofit actions.

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Table 1
Building performance before retrofit.

Building performance indicators	
Total annual heating demand	216.35 [kW h/m^2 yr]
Total annual cooling demand	4.95 [kW h/m^2 yr]
Total annual DHW demand	52.33 [kW h/m^2 yr]
Total annual energy consumption	273.63[kW h/m^2 yr]
% of time with |PMV| > 0.7	91.51

Table 2
Characteristics of external wall insulation materials.

N	Insulation types	Name	*t* Thickness (m)	*U*-value (W/m^2 K)	*c* Cost (€/m^2)
1	Cork	OUTWALL_CORKHIGH3	0.03	1.408	5.55
2		OUTWALL_CORKHIGH4	0.04	1.124	7.18
3		OUTWALL_CORKHIGH5	0.05	0.935	8.98
4		OUTWALL_CORKHIGH6	0.06	0.800	10.77
5		OUTWALL_CORKHIGH7	0.07	0.699	12.23
6		OUTWALL_CORKHIGH8	0.08	0.621	14.36
7		OUTWALL_CORKHIGH9	0.09	0.559	16.78
8		OUTWALL_CORKHIGH10	0.1	0.508	17.95
9	EPS	OUTWALL_EPSLOW3	0.03	0.800	7.64
10		OUTWALL_EPSLOW4	0.04	0.621	8.34
11		OUTWALL_EPSLOW5	0.05	0.508	9.03
12		OUTWALL_EPSLOW6	0.06	0.429	9.74
13		OUTWALL_EPSLOW7	0.07	0.372	10.44
14		OUTWALL_EPSLOW8	0.08	0.328	11.15
15		OUTWALL_EPSLOW9	0.09	0.293	12.35
16		OUTWALL_EPSLOW10	0.1	0.265	13.68
17	XPS	OUTWALL_XPSLOW3	0.03	0.800	9.65
18		OUTWALL_XPSLOW4	0.04	0.621	11.64
19		OUTWALL_XPSLOW5	0.05	0.508	14.43
20		OUTWALL_XPSLOW6	0.06	0.429	17.22
21		OUTWALL_XPSLOW7	0.07	0.372	19.34
22		OUTWALL_XPSLOW8	0.08	0.328	22.78
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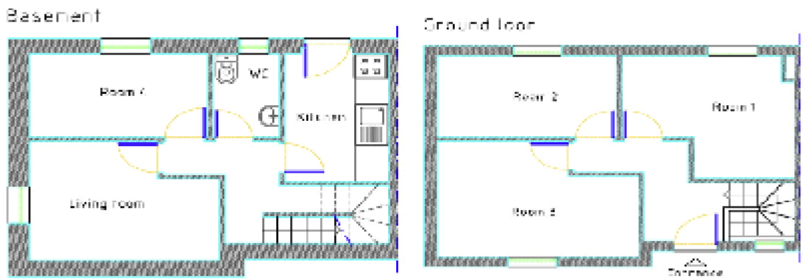

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18		OUTWALL_XPSLOW4	0.04	0.621	11.64
19		OUTWALL_XPSLOW5	0.05	0.508	14.43
20		OUTWALL_XPSLOW6	0.06	0.429	17.22
21		OUTWALL_XPSLOW7	0.07	0.372	19.34
22		OUTWALL_XPSLOW8	0.08	0.328	22.78
23		OUTWALL_XPSLOW9	0.09	0.293	24.43
24		OUTWALL_XPSLOW10	0.1	0.265	26.78

Table 3
Characteristics of roof insulation materials.

N	Insulation types	Name	*t* Thickness (m)	*U*-value (W/m² K)	*c* Cost (€/m²)
1	XPS (extruded polystyrene	ROOF_XPS3	0.03	0.800	9.65
2	stone wool)	ROOF_XPS4	0.04	0.621	11.64
3		ROOF_XPS5	0.05	0.508	14.43
4		ROOF_XPS6	0.06	0.429	17.22
5		ROOF_XPS7	0.07	0.372	19.34
6		ROOF_XPS8	0.08	0.328	22.78
7	EPS (expanded polystyrene)	ROOF_EPS3	0.03	0.800	4.32
8		ROOF_EPS4	0.04	0.621	5.60
9		ROOF_EPS5	0.05	0.508	6.87
10		ROOF_EPS6	0.06	0.429	8.14
11		ROOF_EPS7	0.07	0.372	9.43
12		ROOF_EPS8	0.08	0.328	10.70
13	Polyurethane	ROOF_PU3	0.03	0.658	8.34
14		ROOF_PU4	0.04	0.508	10.98
15		ROOF_PU5	0.05	0.413	13.40
16		ROOF_PU6	0.06	0.348	15.30
17		ROOF_PU7	0.07	0.301	17.86
18		ROOF_PU8	0.08	0.265	20.18

Table 4
Characteristics of windows.

N	Name	Thermal transmittance (W/m² °C)	Effective solar energy transmittance (%)	Cost (€/m²)
1	SGSILVER	1.05	28.80	58.70
2	SGPLANISOLGREEN	1.16	26.50	67.82
3	SGCLIMATOP	0.52	58.50	102.25

Finally, when the "percentage of discomfort hours" over the whole year is optimized, another solution configuration is obtained, which leads to an energy savings objective function not far from its optimal value but at a significantly lower cost.

As stated earlier, a Tchebycheff programming approach has been used to compute compromise non-dominated solutions displaying different trade-offs between the objective functions, thus sampling the non-dominated frontier. The non-dominated solution that minimizes the Tchebycheff distance to the ideal solution (taken as the unreachable reference point) is then computed for different combinations of objective function weight coefficients using a modified version of the *bintprog* function in MATLAB, which makes the construction of the non-dominated frontier possible. As the first step, the first two objective functions (retrofit cost and energy savings) are considered simultaneously, and then the third objective (percentage of discomfort hours) is added. This stepwise procedure intends to make a better constructive use of the 2-D and 3-D graphical representation of the non-dominated frontier in order to unveil and further discuss the corresponding solutions and trade-offs at stake between the competing objectives.

Fig. 3 shows the non-dominated solutions for the first two objectives. Fig. 4 demonstrates how the objective values change in relation with the specific value of the weights (each point depicts the compromise obtained for a different combination of weight values). This figure clearly shows the competitive nature of objective functions energy savings and retrofit costs. As the weight on energy saving (p_2) increases, the set of actions leading to higher energy savings and at the same time higher cost are selected.

After adding the third objective function (TPMVD), the compromises corresponding to different weight coefficient values are illustrated in Fig. 5 and Table 7. For intermediary values of the weight coefficients, several solutions are obtained that favour each objective function at a higher or lower level depending on the specific values that have been selected. From this figure it is seen that the solutions leading to more energy savings or higher retrofit cost do not necessarily lead to a lower percentage of discomfort hours, and accordingly better thermal comfort. This case highlights the advantage of a true multi-objective optimization model, which is able to provide the DM a thorough understanding of the decision situation, namely concerning the trade-offs at stake and shedding light on the potentiality of each investment option.

Table 5
Characteristics of solar collector systems.

N	Type	Name	Generation efficiency (%)	Collector area (m²)	Cost (€/m²)
1	Flat	FC702	70	2	700
2	collector	FC802	80	2	800
3		FC704	70	4	1250
4		FC804	80	4	1600

Table 6
Non-dominated solutions that optimize each objective (individual optima to each objective function in bold italic).

Solution	Type of solution	ReCost (€)	ES (kW h/year)	TPMVD	EWAL	ROF	WIN	SC
S1	[min] ReCost	***2843.15***	9065.06	83.79	1	7	1	1
S2	[max] ES	7245.52	***12,792.15***	93.07	24	18	3	4
S3	[min] TPMVD	4374.83	12,284.48	***82.69***	16	1	2	1

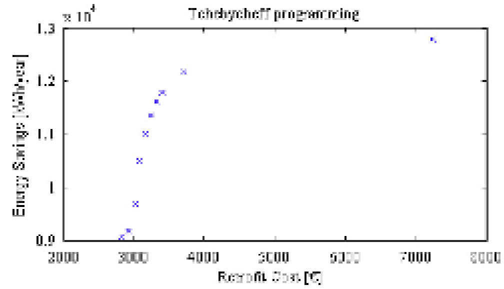

Fig. 3. Multi-objective solutions for the building retrofit strategies (two objective functions).

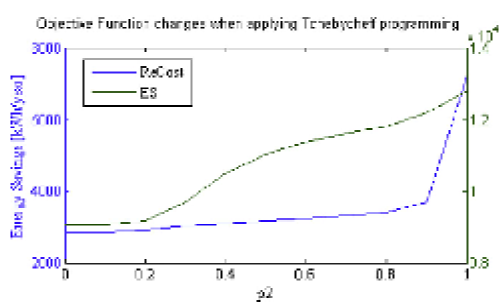

Fig. 4. Objective functions changes with respect to weights in the Tchebycheff formulation.

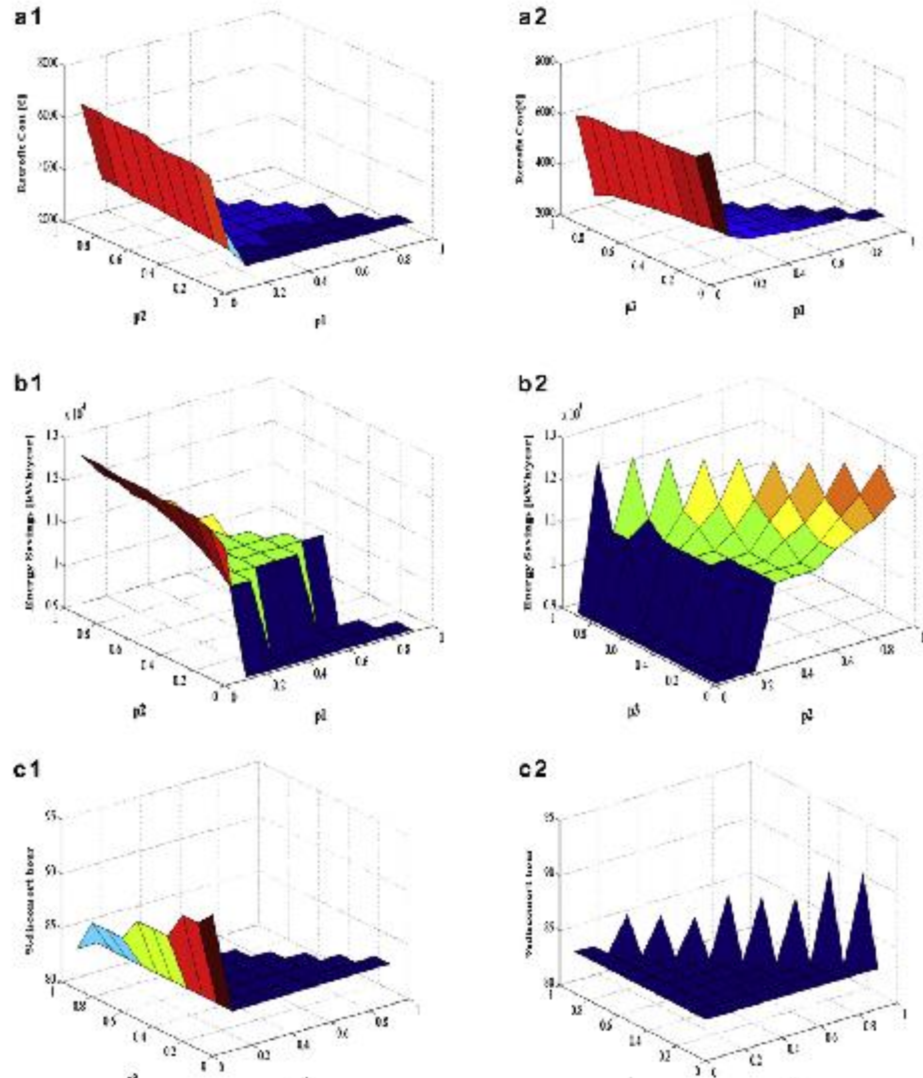

Fig. 5. Compromise solutions for different weights: Retrofit cost vs energy saving (a1) and discomfort hours (a2), energy saving vs retrofit cost (b1), and discomfort hours (b2), discomfort hours vs retrofit cost (c1), and energy saving (c2).

The results of the proposed approach demonstrate the practicability as well as its strength to provide decision support in the problem of selecting building retrofit actions. This approach allows for the simultaneous consideration of all available combination of retrofit actions, as well as the consideration of any logical, physical, and technical constraints.

Finally, the results of the application of a Tchebycheff programming technique to compute solutions to the case study shows the feasibility of this methodology to reveal the trade-offs at stake and find well balanced strategies for retrofitting of buildings to be presented to a DM in the framework of a decision support process.

APPENDIX F PAPER PUBLISHED AT BUILDING AND ENVIRONMENT JOURNAL: A MULTI-OBJECTIVE OPTIMIZATION MODEL FOR BUILDING RETROFIT STRATEGIES USING TRNSYS SIMULATIONS, GENOPT AND MATLAB

Table 7
Sample of non-dominated solutions obtained using Tchebycheff programming.

z	p1	p2	p3	ReCost (€)	ES (kW h/year)	TPMVD (%)	EWAL	ROF	WIN	SC
0.24	1	0	0	2843	9065.06	83.79	1	7	1	1
0.22	0.9	0.1	0	2843	9065.06	83.79	1	7	1	1
0.22	0.9	0	0.1	2843	9065.06	83.79	1	7	1	1
0.19	0.8	0.2	0	2843	9065.06	83.79	1	7	1	1
0.19	0.8	0.1	0.1	2843	9065.06	83.79	1	7	1	1
0.19	0.8	0	0.2	2843	9065.06	83.79	1	7	1	1
0.27	0.7	0.3	0	3163	11,017.98	83.7785	10	7	1	1
0.17	0.7	0.2	0.1	2843	9065.06	83.79	1	7	1	1
0.17	0.7	0.1	0.2	2843	9065.06	83.79	1	7	1	1
0.17	0.7	0	0.3	2843	9065.06	83.79	1	7	1	1
0.23	0.6	0.4	0	3163	11,017.98	83.7785	10	7	1	1
0.23	0.6	0.3	0.1	3163	11,017.98	83.7785	10	7	1	1
0.14	0.6	0.2	0.2	2843	9065.06	83.79	1	7	1	1
0.14	0.6	0.1	0.3	2843	9065.06	83.79	1	7	1	1
0.14	0.6	0	0.4	2843	9065.06	83.79	1	7	1	1
0.19	0.5	0.5	0	3163	11,017.98	83.7785	10	7	1	1
0.19	0.5	0.4	0.1	3163	11,017.98	83.7785	10	7	1	1
0.19	0.5	0.3	0.2	3163	11,017.98	83.7785	10	7	1	1
0.19	0.5	0.2	0.3	3163	11,017.98	83.7785	10	7	1	1
0.12	0.5	0.1	0.4	2843	9065.06	83.79	1	7	1	1
0.12	0.5	0	0.5	2843	9065.06	83.79	1	7	1	1
0.17	0.4	0.6	0	3243	11,363.03	83.7215	11	7	1	1
0.15	0.4	0.5	0.1	3163	11,017.98	83.7785	10	7	1	1
0.15	0.4	0.4	0.2	3163	11,017.98	83.7785	10	7	1	1
0.15	0.4	0.3	0.3	3163	11,017.98	83.7785	10	7	1	1
0.15	0.4	0.2	0.4	3163	11,017.98	83.7785	10	7	1	1
0.1	0.4	0.1	0.5	2843	9065.06	83.79	1	7	1	1
0.1	0.4	0	0.6	2843	9065.06	83.79	1	7	1	1
0.13	0.3	0.7	0	3324	11,611.67	83.71	12	7	1	1
0.12	0.3	0.6	0.1	3243	11,363.03	83.7215	11	7	1	1
0.12	0.3	0.5	0.2	3243	11,363.03	83.7215	11	7	1	1
0.11	0.3	0.4	0.3	3163	11,017.98	83.7785	10	7	1	1
0.11	0.3	0.3	0.4	3163	11,017.98	83.7785	10	7	1	1
0.11	0.3	0.2	0.5	3163	11,017.98	83.7785	10	7	1	1
0.07	0.3	0.1	0.6	2843	9065.06	83.79	1	7	1	1
0.07	0.3	0	0.7	2843	9065.06	83.79	1	7	1	1
0.1	0.2	0.8	0	3404	11,801.79	83.6986	13	7	1	1
0.1	0.2	0.7	0.1	3404	11,801.79	83.6986	13	7	1	1
0.09	0.2	0.6	0.2	3324	11,611.67	83.71	12	7	1	1
0.09	0.2	0.5	0.3	3324	11,611.67	83.71	12	7	1	1
0.08	0.2	0.4	0.4	3243	11,363.03	83.7215	11	7	1	1
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0.08	0.2	0.1	0.7	3163	11,017.98	83.7785	10	7	1	1
0.05	0.2	0	0.8	2843	9065.06	83.79	1	7	1	1
0.06	0.1	0.9	0	3707	12,185.52	83.6872	15	7	2	1
0.06	0.1	0.8	0.1	3707	12,185.52	83.6872	15	7	2	1
0.06	0.1	0.7	0.2	3570	12,065.51	83.71	14	7	2	1
0.06	0.1	0.6	0.3	3570	12,065.51	83.71	14	7	2	1
0.05	0.1	0.5	0.4	3486	11,949.36	83.6986	14	7	1	1
0.05	0.1	0.4	0.5	3404	11,801.79	83.6986	13	7	1	1
0.04	0.1	0.3	0.6	3324	11,611.67	83.71	12	7	1	1
0.04	0.1	0.2	0.7	3243	11,363.03	83.7215	11	7	1	1
0.04	0.1	0.1	0.8	3163	11,017.98	83.7785	10	7	1	1
0.02	0.1	0	0.9	2843	9065.06	83.79	1	7	1	1
0	0	1	0	7246	12,792.15	93.0708	24	18	3	4
0	0	0.9	0.1	6754	12,770.83	91.6438	24	16	2	4
0	0	0.8	0.2	6754	12,770.83	91.6438	24	16	2	4
0	0	0.7	0.3	6690	12,709.36	89.0639	24	3	2	4
0	0	0.6	0.4	6690	12,709.36	89.0639	24	3	2	4
0	0	0.5	0.5	6690	12,709.36	89.0639	24	3	2	4
0	0	0.4	0.6	6421	12,647.81	86.8265	24	2	2	4
0	0	0.3	0.7	6421	12,647.81	86.8265	24	2	2	4
0	0	0.2	0.8	6421	12,647.81	86.8265	24	2	2	4
0	0	0.1	0.9	6228	12,522.85	83.6986	24	1	2	4
0	0	0	1	4375	12,284.48	82.6872	16	1	2	1

4. Conclusions

One of the best opportunities to improve energy efficiency of buildings is during retrofit. One of the key steps in building retrofit is the selection of retrofit actions among a large number of possibilities, which are derived from a large set of materials for different purposes and displaying different characteristics. This problem is a multi-objective optimization problem, characterized by the existence of multiple and competing objectives to appraise the merit of distinct solutions, which are not predefined but are implicitly defined by a set of parameters and constraints that should be taken into account to reach the best possible one.

This paper described an optimization methodology based on a combination of TRNSYS, GenOpt and a multi-objective optimization algorithm developed in MATLAB. The proposed approach was applied to a real-world case study, and the results demonstrate its practicability to provide decision support in an actual setting. This allows explicitly for the simultaneous consideration of all available combinations of alternative retrofit actions.

The further consideration of all the possibilities that the DM has available for building retrofit (e.g. HVAC systems and renewable energy sources), as well as all the objective that he/she may wish to optimize (CO_2 emission, social objective, etc.) may lead to a combinatorial explosion of the decision space, thus making the solving procedure extremely difficult and time-consuming. In this case, other optimization techniques, namely evolutionary multi-objective algorithms may become necessary for tackling the problem. Besides, using approximation methodologies like regression modelling of the building in the optimization part would be of interest.

Acknowledgements

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Chapter 11
State-of-the-art on retrofit strategies selection using multi-objective optimization and genetic algorithms

Ehsan Asadi[1], M. Gameiro da Silva, C. Henggeler Antunes , Luís Dias.

Abstract The retrofit of a building involves not just the fulfillment of functional requirements, but also considerations such as investment costs, energy consumption, environmental impact and occupant wellbeing. Careful long-term decisions in the retrofit and operation of buildings can significantly improve their thermal performance and thus reduce their consumption of energy. Moreover, they can improve indoor environmental quality in buildings. Alternative building energy conservation measures, standards compliance and economic optimization can be evaluated using available energy analysis and decision aid techniques. These may range from simplified energy analysis methods for approximate energy use estimates to detailed computerized hourly simulation coupled with decision aid techniques. This chapter reviews the research and development in the decision support processes in building retrofit. Special attention is devoted to the methodologies using multi-objective optimization and genetic algorithms. Accordingly the decision methodologies are broadly separated into two main categories: approaches in which alternatives are explicitly known a priori and approaches in which alternatives are implicitly defined by an optimization model. The advantages and drawbacks of the various methods in each category are also discussed.

11.1 Introduction

The building sector is the largest user of energy and CO_2 emitter in Europe and the US. Besides it is responsible for about 40% of the EU's and US total final energy consumption. Even if all future buildings were to be built so that their energy demand was very low, this would still only mean that the increase in energy demand would be reduced and it would not reduce the present demands (Asadi et al., 2012a). For many years to come, only measures taken in existing buildings will have a significant effect on the total energy demand in the building stock. There-

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fore, rapid enhancement of energy efficiency in existing buildings is essential for a timely reduction in global energy use and promotion of environmental sustainability.

During the last decade, many governments and international organisations have put significant effort towards energy efficiency improvement in existing buildings, as evidenced by the EU Energy Efficiency Action Plan and President Obama's Better Buildings Initiative, among others (WhiteHouse, 2011). In EU, the cornerstone of the European energy policy has an explicit orientation to the conservation and rational use of energy in buildings as the energy performance of building directive (EPBD) 2002/91/EC and its recast (EPBD) 2010/31/EU indicate (EC, 2002, EC, 2010). The EPBD's main objective is to promote the cost-effective improvement of the overall energy performance of buildings. One of the best opportunities to do so would be during building retrofit.

Existing buildings retrofit offer many challenges and opportunities. The main ch allenge is that many uncertainties are at stake, such as climate change, services change, human behaviour change, government policy change, etc., all of which directly affect the selection of retrofit technologies and hence the success of a retrofit project. The sub-systems in buildings are highly interdependent. Different retrofit measures may have different impacts on distinct building sub-systems due to these interdependencies, which make the selection of retrofit technologies very complex. Dealing with these uncertainties and system interactions is a considerable technical challenge in any sustainable building retrofit project. Other challenges may include financial limitations and barriers, perceived long payback periods, and interruptions to operations of buildings. The willingness of building owners to pay for retrofits is another challenge if there is no financial support from the government, particularly since the issue of "split incentives" is often a key factor because the retrofit cost generally falls to the building owner whereas the benefit often flows primarily to the tenants. On the other hand, building retrofit offers great opportunities for improved energy efficiency, increased staff productivity, reduced maintenance costs and better indoor comfort. It may also help to improve a nation's energy security and corporate social responsibility, reduce exposure to energy price volatility, create job opportunities and make buildings more liveable(Ma Z. et al., 2012).

According to Ma et al. (2012), the overall process of a building retrofit can be divided into five major steps (Fig. 1). The first phase is the project setup and pre-retrofit survey. In this phase the building owners, or their agents, first need to define the scope of the work and set project targets. The available resources to frame the budget and program of work can then be determined. A pre-retrofit survey may also be required in order to better understand building operational problems and the main concerns of occupants.

The second phase comprises an energy audit and performance assessment (and diagnostics). Energy auditing is used to analyze building energy data, understand building energy use, identify areas with energy waste, and propose no cost and low cost energy conservation measures (ECMs). Performance assessment is em-

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ployed to benchmark building energy use by means of selected key performance indicators or green building rating systems. Diagnostics can be used to identify inefficient equipment, improper control schemes and any malfunctions in the building operation.

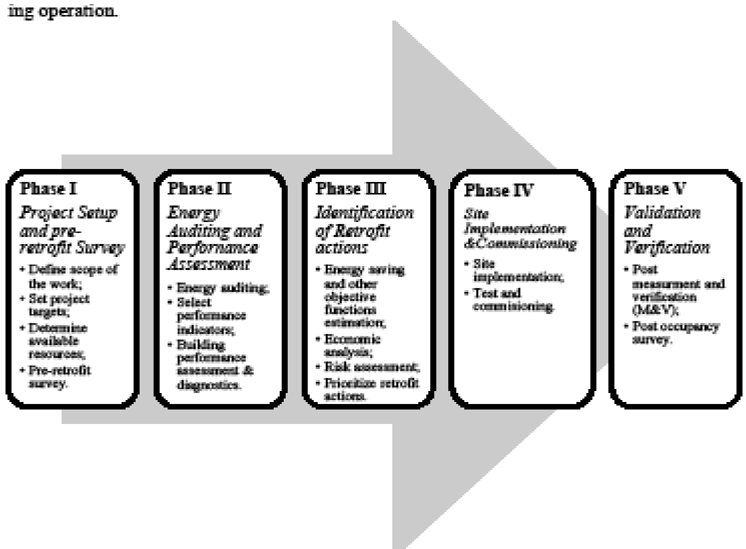

Figure 1 Key phases in a sustainable building retrofit program (Ma Z. et al., 2012).

The third phase is the identification of retrofit actions. By using appropriate energy models, economic analysis tools and risk assessment methods, the performance of a range of retrofit alternatives can be assessed quantitatively. The retrofit alternatives can then be prioritized based on the relevant energy-related and non-energy-related objectives such as the increase in retrofitted building market value.

The fourth phase is site implementation and commissioning. The selected retrofit measures will be implemented on-site. Test and commissioning is then employed to tune the retrofit measures to ensure the building and its services systems operate in an optimal manner. It is worth noting that the implementation of some retrofit measures may necessitate significant interruption to the building and occupants operations.

The final phase is validation and verification of energy savings. Once the retrofit measures are implemented and well-tuned, standard measurement and verification methods can be used to verify energy savings. A post occupancy survey is also needed to understand whether the building occupants and building owners are satisfied with the overall retrofit result.

This chapter aims at providing an overview of recent research and development in the third phase that is identification of retrofit actions by paying special attention to the methodologies using multi-objective optimization and genetic algorithms.

11.2 Building Retrofit- methodologies and strategies

Nowadays, a great number of innovative technologies and energy efficiency measures for building retrofit exist. The main issue is to identify those that will prove to be the more effective and reliable in the long term. When choosing among a variety of proposed measures, the Decision Maker (DM) has to reconcile environmental, energy related, financial, legal regulation and social factors to reach the best possible compromise to satisfy the final occupant needs. In practice, seeking such a solution is mainly attempted via two main approaches (Diakaki et al., 2008).

In the first approach, an energy analysis of the building is carried out and several alternative scenarios predefined by a building expert are developed and evaluated mainly through simulation (Krarti, 2000). Although many sophisticated energy simulation programs (e.g., TRNSYS, Energy Plus) are valuable to study the impact of alternative scenarios on building performance, the iterative trial-and-error process of searching for a better retrofit action is time-consuming and ineffective due to inherent difficulty in exploring a large decision space.

The second approach, which is the focus of this paper, includes decision aid techniques that are usually combined with simulation to assist reaching a final decision among a set of alternative actions. In this chapter a conceptual distinction is made between multi-criteria and multi-objective models, according to the scientific literature. In a multi-criteria model, the finite set of alternatives (e.g. three different types of windows) is explicitly known a priori, in general predefined by the building expert, to be evaluated according to multiple (quantitative and/or qualitative) criteria that may be expressed in different types of scales. In multi-objective optimization (mathematical programming) models, the set of feasible solutions (e.g. the thickness of the wall) is implicitly defined by the decision variables and the constraints, and the evaluation aspects of the merit of those solutions are operationalized through objective functions to be optimized.

Jaggs and Palmar (2000), Flourentzou and Roulet (2002), and Rey (2004) proposed MC-based approaches for the evaluation of retrofitting scenarios. Kaklauskas et al. (2005) developed a multivariate design method and multi-criteria analysis for building retrofit, determining the significance, priorities and utility degree of building retrofit alternatives and selecting the most recommended variant. Juan et al. (2009) developed a genetic algorithm-based decision support system for

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housing condition assessment that suggests optimal retrofit actions considering the trade-off between cost and quality.

These lines of research have allowed addressing many problems as far as buildings retrofit is concerned. However, most of them consider that a list of predefined and pre-evaluated alternative variants of the building retrofit options is given. In case a small number of such solutions have been defined, there is no guarantee that the solution finally reached is the best one (from the DM's perspective). On the opposite, when a large number of solutions are defined the required evaluation and selection process may become extremely difficult to handle.

The problem faced by the DM may also be framed as a multi-objective optimization model, in which multiple and competing objective functions are formulated to assess feasible alternatives, which are not predefined but are implicitly defined by a set of constraints.

Based on an extensive literature review and Fig. 1, it could be stated that most methodologies for decision support in energy management and sustainability in building sector follow three major steps:

1. Definition of main objectives/criteria of the project;
2. Definition of alternative retrofit actions, either by stating them explicitly or defining a comprehensive mathematical model;
3. Selection of assessment methodologies adequate to the model.

Accordingly, the remainder of this chapter overviews the main objectives in the course of building retrofit. Different building retrofit technologies are reviewed in section 1.2.2. Furthermore, retrofit action selection methodologies are discussed in chapter 1.2.3. Finally, section 1.2.4 and 1.3 summarizes conclusions and discusses issues for future research and development.

11.2.1 Objectives in Building Retrofit

The objectives for building retrofit can be either quantitative or qualitative and can be divided into four main categories depicted in Fig 2. (Kolokotsa et al., 2009).

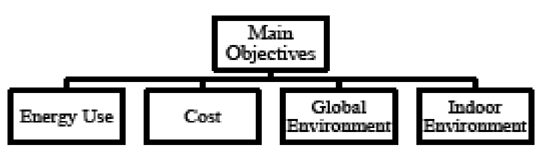

Figure 2 The main objectives for building retrofit (Kolokotsa et al., 2009).

More specifically, regarding energy use (primary or final), the following objectives have been utilized (Kolokotsa et al., 2009):

- heating and cooling load for conditioned buildings (D'Cruz and Radford, 1987, Bouchlaghem, 2000);
- normalized annual energy consumption and energy use for heating in kWh/m^2 (Rey, 2004, Zhu, 2006);
- annual electricity use in kWh/m^2 (Rey, 2004);
- embodied energy (Chen et al., 2006);
- energy and time consumption index (ETI) (Chen et al., 2006);
- energy savings due to building retrofit in kWh/year (Gholap and Khan, 2007, Asadi et al., 2012a)

Regarding costs, the following objectives have been used:

- direct costs and initial investment costs (Rosenfeld and Shohet, 1999);
- cost of retrofit (Asadi et al., 2012a);
- economic life span (Rosenfeld and Shohet, 1999);
- annual ongoing maintenance charges (Rosenfeld and Shohet, 1999, Rey, 2004);
- annual ongoing charges (Rey, 2004);
- net present value (NPV) of the energy investment (Martinaitis et al., 2007);
- internal rate of return (IRR) of the energy investment (Martinaitis et al., 2004);
- cost of conserved energy (CCE) (Martinaitis et al., 2004);
- life cycle cost (LCC) (Wang et al., 2005);

As far as global environment is concerned, the objectives usually set are:

- annual emissions GWP (global warming potential in $kgeqCO_2/m^2$) (Rey, 2004);
- reduction potential of global warming emissions (Alanne, 2004);
- life cycle environmental impact (Wang et al., 2005);
- acidification potential in $kgeqSO_2/m^2$ (Rey, 2004, Alanne et al., 2007);
- water use (Alanne et al., 2007).

Indoor environmental quality and comfort have subcategories for the evaluation of thermal sensation, visual comfort, indoor air quality and acoustic comfort (Kolokotsa et al., 2009). More specifically, regarding thermal comfort, the following objectives and indicators have been used:

- PMV-PPD thermal comfort indices based on ISO-7730 standard (ISO, 2005)
- dry resultant temperature for unconditioned buildings (Bouchlaghem, 2000);
- indoor temperature and humidity (Jaggs and Palmer, 2000);
- discomfort hours during summer or winter (Roulet et al., 2002);
- daily overheating in K (Rey, 2004);
- effective draught temperature index (Rutman et al., 2005);

- summer thermal discomfort severity index, which indicates the severity of excessive mean radiant temperature during summer (Becker et al., 2007)
- total percentage of cumulative time with discomfort (Asadi et al., 2012b).

For visual comfort, the assessment objectives can be:

- daylight availability (Radford and Gero, 1980b);
- lighting and visual comfort (e.g. EPIQR method, see (Bluyssen and Cox, 2002, Rey, 2004));
- daylight factor (Rey, 2004);
- discomfort glare severity indicator, which indicates the annual severity of excessive discomfort glare (Becker et al., 2007).

Indoor air quality is generally assessed via:

- CO_2 concentration index (Doukas et al., 2007);
- maximum ratio between the mean concentration of a contaminant over the occupancy period and the contaminant's threshold limit value for short-term or long term exposure (Blondeau et al., 2002);
- ventilation rates (Blondeau et al., 2002).

Acoustic comfort objectives include:

- noise level at workplace in dB (Rey, 2004);
- noise rating index (Rutman et al., 2005).

These objectives are, in general, competitive, in the sense that it is impossible to find a global solution to optimize all of them simultaneously. For this reason, several decision aid approaches have been developed for addressing the mentioned problem, namely based on multi-criteria and multi-objective models. A review of descriptors usually used to assess the indoor environmental quality of confined compartments is presented in (Gameiro da Silva, 2002). Some other descriptors not included in the previous list, but suitable for the assessment of quality of indoor environment are:

- Operative Temperature (T_o) and Equivalent Temperature (T_{equi}), for thermal comfort. The percentage of permanence of indoor thermal conditions inside the comfort band defined in an adaptive comfort chart (ISO, 2007), where T_o is depicted versus the outdoor mean running temperature, is a suitable indicator of the performance of buildings without mechanical systems to provide comfortable conditions to occupants.
- Average illuminance level in the working/activity plan (ISO, 2002), as regards visual comfort.
- Percentage of Dissatisfied with IAQ. It may be calculated from the concentration of CO_2 using the expressions presented in (CEN, 1998)
- Noise equivalent level L_{Aeq} during the working period, in dB(A)
- Reverberation T of the room along the frequency spectrum of noise
- Sound Transmission Index (STI)

11.2.2 Building Retrofit Technologies

According to Ma et al. (2012) the retrofit technologies can be categorized into three groups: supply side management, demand side management, and change of energy consumption patterns, i.e. human factors. **Fig. 3** illustrates major possible retrofit technology types that can be used in building applications.

The retrofit technologies for supply side management include electrical system retrofits and the use of renewable energy, such as solar hot water, solar photovoltaic (PV), wind energy, geothermal energy, etc., as alternative energy supply systems to provide electricity and/or thermal energy for buildings. In the last years, there has been an increasing interest in the use of renewable energy technologies as building retrofit solutions due to the increased awareness of environmental issues.

The retrofit technologies for demand side management consist of strategies to reduce building heating and cooling demand, and the use of energy efficient equipment and low energy technologies. The heating and cooling demand of a building can be reduced through retrofitting the building envelope and the use of other advanced technologies such as air tightness, windows shading, etc.

Low energy technologies may include advanced control schemes, natural ventilation, heat recovery, thermal storage systems, etc. (Ma Z. et al., 2012).

Figure 3 Main categories of building retrofit technologies (Ma Z. et al., 2012).

11.2.3 Assessment Methodologies

In the building retrofit, the assessment phase involves the evaluation of ECM or retrofit actions versus the selected objective functions mentioned in section 1.2.1 with respect to logical, physical and technical constraints concerning building retrofit strategies.

Therefore, the assessment procedure is an iterative procedure influenced by the objectives, the alternative actions, and set of constraints. This iterative procedure is illustrated in Fig 4.

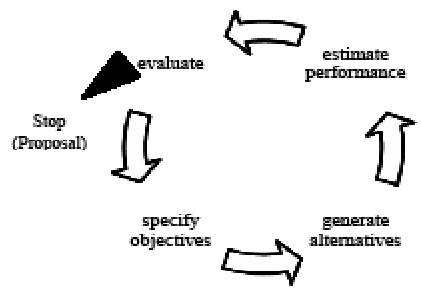

Figure 4 The iterative decision support process (Alanne, 2004)

The methodologies for assisting decision making in the appraisal of retrofit actions according to multiple, generally conflicting and incommensurate, evaluation aspects may be distinguished into two main approaches (Fig. 5), according to the distinct made above of models in which alternatives are explicitly known a *priori* and alternatives are *implicitly* defined in the setting of an optimization model.

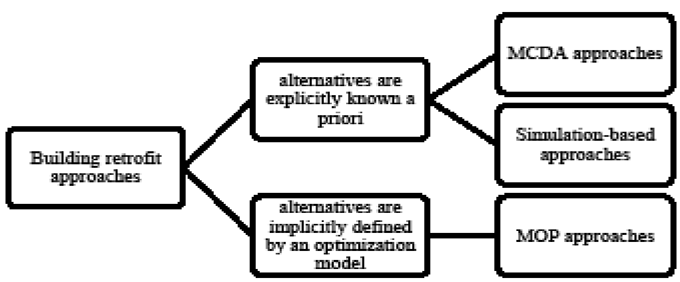

Figure 5 Categorization of methodological approaches for building retrofit

These approaches are subcategorized and analyzed in the following sections.

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11.2.3.1 MCDA approaches (alternatives explicitly known a *priori*)

In this category there is a relatively small list of alternatives to choose from. In general an impact matrix is developed in close cooperation between the problem owners and experts, which expresses in a given scale the performance of each alternative for each evaluation criterion. Several methodological approaches may then be used to combine this information with the DM's preferences in order to reach a final recommendation that establishes a good compromise between the evaluation criteria.

Multi-criteria Decision Analysis Approaches

Traditionally, the selection of energy alternatives and retrofit actions was based only on cost optimization. The need to incorporate the environmental and social impacts of different alternatives and viewpoints of different actors in the analysis promoted the use of multi-criteria decision analysis methods. A wide range of MCDA methods have been applied in the energy planning area (Diakoulaki et al., 2005). In an MCDA approach, it is necessary to define the problem clearly, identify the actors involved in the decision making process and their values, develop a coherent set of evaluation criteria and establish realistic alternatives. An MCDA method is selected to aggregate the performance of each alternative according to the set of criteria using the preferences elicited from the DM through technical parameters. Most MCDA methods require weighting of the criteria, although the meaning of weights may be very different from method to method. The application of MCDA methods may provide a selection of the best alternative, a ranking of the alternatives or a sorting of the alternatives in pre-defined ordered categories of merit. The most representative MCDA methods may be included into the broad classifications of methods developing an overall synthesis value (e.g., multi-attribute value/utility function approaches, AHP) and outranking based approaches (e.g.,ELECTRE, PROMETHEE).

Blondeau et al. (2002) used both combinatorial method based on the multiple attribute utility theory (MAUT) and outranking methods to determine the most suitable ventilation strategy of a university building, that is to ensure the best possible indoor air quality and thermal comfort of the occupants, and the lower energy consumption in case of accelerated diurnal or nocturnal ventilation and/or air conditioning. It was shown that the results of the analysis by combinatorial method strongly depend on the definition of the total utility function and the pernicious effects may affect its validity. On the other hand, outranking method most probably allow to best fit the DM's way of thinking but their result is not always as clear as the one obtained with combinatorial method.

Roulet et al. (2002) used principal component analysis, as well as multi-criteria ranking method, based on ELECTRE III and VI algorithms to develop a method for ranking office buildings (ORME: office rating methodology) according to an extended list of parameters, including energy use for heating, cooling and other appliances, impact on external environment, indoor environment quality, and cost. Outranking methods are also used by Rey . The ELECTRE III method is used to rank office building retrofitting strategies.

EPIQR (Energy Performance Indoor Environmental Quality Retrofit Methods for Apartment Building Refurbishment) (Jaggs and Palmer, 2000) and TOBUS (Tool for Selecting Office Building Upgrading Solutions) (Caccavelli and H., 2002) are other tools using MCDA techniques for building retrofit actions selection. The TOBUS method aims at offering a tool for selecting office building's retrofit solutions with respect to multiple criteria. One of the key elements to reach this goal was an assessment of the degree of physical degradation, extent of any degradation, extent of the necessary work to retrofit the building and the costs.
Kaklauskas et al (2005) used multivariant design and MCDA to prioritize and rank the alternative solutions for the refurbishment of a building envelope. The alternatives' significance, utility degree and priority are extracted using this methodology and, as a consequence, the strongest and weakest points of the refurbishment are revealed.

Alanne (2004) combines MCDA and a knapsack (multi-objective) model to support building retrofit. MCDA is used to extract the utilities of the retrofit actions proposed, as well as the total utility versus the selected criteria. The utility scores obtained are then used as weights in a knapsack optimization model to identify the actions that should be undertaken, through the maximization of the objective function (that is utility score achieved by selecting the retrofit action, specified by environmental value and functionality) subject to budget constraints.

Simulation-based Approaches

Simulation-based approaches are either simplified (analytical methods) or detailed (numerical methods) using powerful simulation programs.

In the simulation-based process, a basic model of the building is developed using simulation tools. Then, through an iterative procedure, a series of recommendations are defined using the best construction practice (Horsley et al., 2003). These recommendations may include increase of insulation, change of glazing, etc.

There are a number of detailed building energy simulation packages, such as EnergyPlus, eQuest, DOE-2, ESP-r, BLAST, HVAC-SIM+, TRNSYS, etc. A detailed comparison of the capabilities of 20 building energy simulation packages can be found in **Ref** (Crawley et al., 2008).

For example, TRNSYS is used by Santamouris et al. (Santamouris et al., 2007) to investigate the energy saving potential of green roofs in a nursery school in Greece. EnergyPlus is used by Becker et al (Becker et al., 2007) to assess specific factors of building design elements (window orientation, glazing type, thermal resistance of walls, etc.) and 20 ventilation strategies for schools' energy consumption and efficiency. Zmeureanu (Zmeureanu et al., 1999) employed DOE-2 to estimate the energy savings due to building retrofits.

Although many sophisticated energy simulation programs are valuable to study the impacts of different ECM on building performance, the iterative trial-and-error process of searching for a better solution is time-consuming and ineffective because of the inherent difficulty in exploring a large design space.

The main problem when employing MCDA techniques is that they are applied upon a set of predefined alternative courses of action. In case that a limited number of such alternatives have been defined, there is no guarantee that the solution finally reached is the optimal one. Also, the selection of a representative set of alternatives is usually a difficult problem, while the final solution is heavily affected by these predefined alternatives. On the opposite case, i.e. when numerous alternatives are defined, the required evaluation and selection process may become extremely difficult to handle. In any case, however, the MCDA approach limits the study to a potentially large but certainly finite number of alternatives, when the real opportunities are enormous considering all the available ECM that may be employed (Diakaki et al., 2008).

11.2.3.2 MOP approaches (alternatives implicitly in a mathematical model)

Decision support for improving energy efficiency in buildings problems are also tackled using multi-objective optimization models stated as mathematical programming models with multiple competing objective functions to be optimized being the set of feasible solutions implicitly defined by a set of constraints.

Multi-objective Programming (MOP) Approaches

The modeling of real-world problems generally requires the consideration of distinct axes of evaluation of the merits of potential solutions. Namely in engineering problems, aspects of operational, economical, environmental and quality of service nature are at stake. Therefore, mathematical models must explicitly address these multiple, incommensurate and often conflicting aspects of evaluation as objective functions to be optimized. Besides MOP models enlarge the variety of potential solutions to be considered and enable to grasp the trade-offs between the objective functions helping to reach a satisfactory compromise solution. The essential concept in multi-objective optimization is the one of non-dominated (efficient, Pareto optimal) solutions, that is feasible solutions for which no improvement in all objective functions is possible simultaneously; in order to improve an objective function it is necessary to accept worsening at least another objective function value. In real-world problems, a high number of non-dominated solutions is likely to exist. Fig. 6 illustrates this concept for a problem with two objective functions to be minimized. Although it is the essential concept in MOP, the concept of non-dominated solution is a poor one, in the sense that it lacks discriminative power for decision recommendation purposes. Non-dominated solutions are not comparable between them, so no solution naturally arises as the "final" one. The fact that multi-objective optimization enables the characterization of the non-dominated front and the trade-offs at stake between the objective functions is one of its advantages. However, it is then necessary to reach a final compromise solution for practical implementation of a reduced set of non-dominated solutions for further screening.

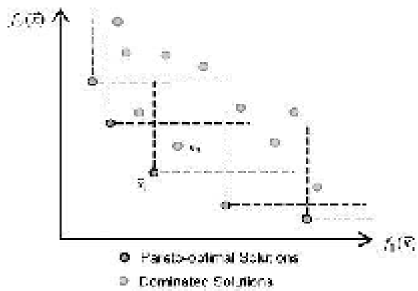

Figure 6 Example of a Pareto set

Pareto optimization was introduced in this area in the 1980s by Radford, Gero and D'Cruz (1980b, 1980a, 1983, 1987), and it is now widely used in building design and less in retrofit optimization. It was used, for example, by Asadi et al.(2012a, 2012b), to optimize the retrofit cost and energy savings of a residential building. Diakaki et al. (2008) developed a MOP model to find alternative measures for improving energy efficiency in buildings. Hamdy et al. (2011) proposed a MOP approach based on Genetic Algorithm (GA) to tackle the problem of designing low-emission cost-effective dwellings. The proposed approach used to minimize the carbon dioxide emissions and the investment cost for a two-story house and its HVAC system. Magnier et al. (2010) used a simulation-based Artificial Neural Network (ANN) to characterize building behavior, and then combined ANN with multi-objective GA for optimization of thermal comfort and energy consumption in a residential house.

Multi-objective Programming (MOP) Approaches using GA

The use of GA to deal with MOP models has gained an increasing relevance due to their ability to work with a population of individuals (solutions) that expectedly converges to the true non-dominated front (Deb, 2001). GA are particularly suitable for tackling hard combinatorial and/or non-linear models, as they are less susceptible to the shape or continuity of the non-dominated front than the classical (mathematical programming) optimization methods. The rationale is that GA deal

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with a population of solutions and the aim is generally the characterization of a non-dominated front. In this setting GA incorporating techniques to preserve the diversity of solutions (for a comprehensive depiction of that front thus unveiling the trade-offs in different regions of the search space) possess advantages compared with the use of "scalarizing" functions, in which a surrogate scalar function aggregating the multiple objectives is optimized, as in traditional mathematical programming approaches. However, it must be noticed that, in real-world problems, this is, in general, "just" a potential non-dominated front (also known as pareto front), classified as such because no other solutions dominating it could be found but no theoretical tools exist, which guarantee their true Pareto optimality.

GAs have been extensively used as search and optimization tools in several real-world problems, such as building energy efficiency problems, due to their flexibility and good performance in exploring the search space. Regarding building applications, GA are frequently used for the optimization of building thermal system design (Wright et al., 2002), HVAC controls (Huang and Lam, 1997, Lu et al., 2005), and chiller energy costs (Chow et al., 2002).

The pseudo algorithm of GA is displayed in **Fig. 7**, and can be described with the following steps:

- First, a random population is created, where each individual represents a solution using some encoding scheme (for instance, binary).
- At each generation, couples of individuals (parents) produce new individuals by gene-crossover and mutation (offspring).
- At the end of each generation, the candidate solutions to be included in the next generation are evaluated using a fitness evaluation function.
- The last two steps operate until the termination condition is met (generally based on the number of generations or on the stagnancy of population fitness).

```
Begin
   INITIALIZE population with random candidate solutions;
   EVALUATE each candidate;
        REPEAT
                 1 SELECT parents;
                 2 RECOMBINE parents;
                 3 MUTATE the resulting offspring;
                 4 EVALUATE new candidates;
                 5 SELECT individuals for the next generation
        UNTIL (TERMINATION CONDITION is satisfied)
END
```

Figure 7 Basic Genetic Algorithm pseudo-code

As a gradient-free method, GA is able to deal with nonlinear functions and to find global optima without being trapped in local ones. Furthermore, it can handle real, discrete, or even discontinuous variables, and be applied to noisy objective functions (Wright et al., 2002, Huang and Lam, 1997).

A main drawback of GA is the high burden whenever it is necessary to make a high number of calls to an evaluation function involving a high computational cost. In building applications, these evaluations are generally estimated by an external simulation program such as CFD or other simulation packages. If accurate results are required, each evaluation can be time consuming, and thus the complete computational process becomes extremely unattractive (Magnier, 2008). For instance, for the two-objective optimization of building floor shape, Wang et al. (2006) used an evaluation tool where each evaluation took 24 seconds (CPU-time). In that case, the total optimization time, which is mainly due to evaluations, was 68 hours. Using simulation software where each evaluation would take several minutes, a similar optimization would result in a total optimization time of several months. This shortcoming should be dealt with before being able to take full advantage of GA in building energy efficiency problems.

Genetic Algorithm Integrating Neural Network (GAINN) is one of the solutions to the above mentioned problem. The main idea of GAINN is to benefit from the rapidity of evaluation provided by ANN as well as the optimization power of the GA. The procedure is to first use an ANN to approximate the system being studied, and then use this ANN within the GA as the objective function. The outcome is a drastic reduction of the simulation time, while keeping an acceptable quality and reliability in the solution process. The complete workflow of GAINN is illustrated in Fig. 8, and is divided in three steps. First, a base software or experimental set-up is used to generate a database of cases. Once the database is created, it can be used to train and validate the ANN. The ANN is then integrated into the GA as the objective function, so the GA can run with almost instantaneous evaluation of individuals. The GA optimization finally provides the non-dominated solution set (Magnier and Haghighat, 2010).

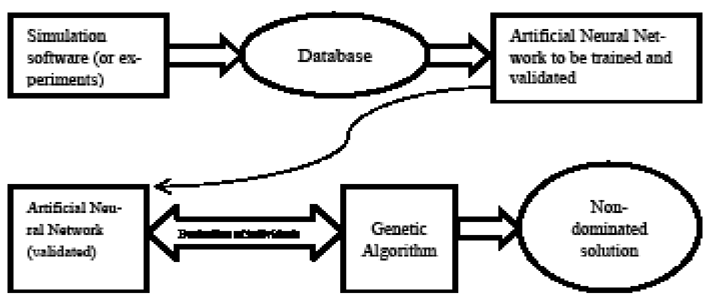

Figure 8 GAINN framework (Magnier and Haghighat, 2010)

GAINN was first used in building engineering for the optimization of chillers control (Chow et al., 2002). This study introduced the methodology to the building field, and proved its efficiency in terms of accuracy and reduction of the total optimization time. Later, GAINN has been successfully applied in other studies, such as Zhou(2007), combined with Computational Fluids Dynamics, and Conraud (2008), combined with ESP-r.

Recently this approach was used by Magnier et al.(2010) using a simulation-based ANN to characterize building behavior, and then the ANN model was combined with a multi-objective GA to optimize thermal comfort and energy consumption in a residential building.

According to the previous studies, the GAINN methodology can be very efficient for building application. Due to the ANN evaluation inside the GA, a significant amount of time can be saved, while keeping the optimization reliable. One main limitation of GAINN is that the optimization results rely on the ANN accuracy. If the ANN is not 100% accurate, results could be affected and optimal solutions could be missed.

Another major drawback regarding how GAINN methodology has been applied so far is the handling of multiple objectives. In the great majority of previous studies, multiple objectives were handled by using an aggregate weighted-sum scalar function. This method suffers from many limitations, such as being dependent on stated assumptions and on the initial situation. It also provides no guarantee to reach the best compromise solution according to the underlying preferences associated with the specification of weights.

11.2.4 Discussion

In this chapter an overview of recent research and development related to evaluation of different retrofit technologies for building applications is provided.
The major findings from previous studies are as follows:

- A large number of innovative technologies and energy efficiency measures for building retrofit exist. The main issue is to identify those that will prove to be the more effective and reliable in the long term.
- The building retrofit assessment procedure is an iterative procedure influenced by the objectives, the alternative actions, and the sets of constraints.
- The methodologies involving multiple evaluation aspects of potential solutions for decision support in the assessment of retrofit action may be distinguished into two main approaches: approaches in which alternatives are explicitly known a priori (MCDA) and approaches in which alternatives are implicitly defined within an optimization model (MOP).
- Appropriate problem structuring methods, selection of evaluation criteria, definition of representative alternative courses of action and preference

elicitation techniques are essential in MCDA approaches to select the most effective retrofit strategies.

- MCDA approaches consider that a list of predefined intervention solutions is given for which the performance in multiple (quantitative or qualitative) criteria is known at the outset. In case a small number of such solutions have been defined, there is no guarantee that the solution finally reached is the best one (from the DM's perspective). On the other hand, when a large number of solutions are defined the required evaluation and selection process may become extremely difficult to handle.
- Recently more attention has been paid to the use of MOP techniques for the problem of improving energy efficiency in buildings. These approaches based on comprehensive mathematical models aim at providing a thorough characterization of the trade-offs between different objectives.
- The use of GA to deal with MOP models for building retrofit decision support has gained an increasing relevance due to its ability to deal with complex mathematical models and avoid being trapped in local non-dominated solutions.
- A major drawback of the application of GA in building efficiency improvement is the high number of calls to evaluation function associated with physical parameters that is generally estimated by an external simulation program such as CFD or other simulation software. If accurate results are required, each evaluation can be time consuming and thus the complete computational process becomes extremely unattractive.
- GAINN is one of the techniques to deal with this problem by approximating the system under study by an ANN whose results are then used within the GA.

11.3 Conclusion

In face of a large set of choices for retrofitting a building, the main issue is to identify those that prove to be the most effective in the long term. When choosing among a variety of proposed measures, the DM (the building expert) has to reconcile environmental, energy, financial, legal regulation and social factors to reach the best possible compromise solution to satisfy the final occupant needs. Therefore, MCDA and MOP models are essential tools to assist the DM in rationalizing the comparison between non-dominated solutions and assess the trade-offs at stake between those distinct evaluations aspects.

Thus, there is a need for further development of decision aid systems based on MCDA and MOP to support building experts in the application of their expertise, and assist less-experienced decision makers, while taking into account the continuous development of technological advances in energy efficient solutions.

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