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UNIVERSIDADE Ð COIMBRA

Hermano Joaquim dos Santos Bernardo

DECISION SUPPORT IN ENERGY PERFORMANCE ASSESSMENT OF SCHOOL BUILDINGS

PhD thesis in Sustainable Energy Systems supervised by Professor Carlos Alberto Henggeler de Carvalho Antunes and Professor Adélio Manuel Rodrigues Gaspar submitted to the Department of Mechanical Engineering, Faculty of Science and Technology, University of Coimbra

December 2022

Faculdade de Ciências e Tecnologia
da Universidade de Coimbra

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Abstract

Energy management in school buildings depends on several technological, social, and organizational factors, resulting in a complex situation away from the usual engineering-focused approach. This thesis aims at presenting the development of a holistic rating system considering multiple and, in general, conflicting and incommensurate aspects that influence energy performance of schools, while taking also into account non-energetic aspects.

An approach combining Soft Systems Methodology and Value Focused Thinking was used to structure the fundamental objectives to be operationalized as criteria in a Multi-Criteria Decision Aid model. The ELECTRE TRI method, which is devoted to sorting problems under multiple evaluation criteria, was used to assign the schools into categories of merit according to their energy performance. The model was developed and applied to a set of eight secondary schools, and performance indicators were obtained in the framework of a research and development project resulting from a partnership involving a facilities management company and three academic research groups. The IRIS software allowed inferring robust conclusions by indicating the range of categories each alternative can be classified into, considering the decision maker's preferences, captured by ELECTRE TRI parameters.

The results show that this constructive process allows for the decision makers to deepen their knowledge on the situation under analysis, and eventually adapt preferences to exploit further outcomes, and reach more informed courses of action concerning interventions in buildings to improve their energy performance.

Keywords

Energy efficiency; energy performance; school buildings; problem structuring methods; multi-criteria decision aid.

Resumo

A gestão de energia em edifícios escolares depende de diversos fatores tecnológicos, sociais e organizacionais, resultando numa situação complexa que é fundamentalmente diferente de uma abordagem habitual em engenharia. Esta tese apresenta o desenvolvimento de um sistema de classificação considerando os múltiplos aspetos, geralmente incomensuráveis e conflituosos entre si, que têm influência no desempenho energético de edifícios escolares, tendo ainda em consideração aspetos não energéticos.

Uma abordagem combinada, recorrendo a *Soft Systems Methodology* e *Value Focused Thinking*, foi utilizada para estruturar os objetivos fundamentais que foram posteriormente operacionalizados como critérios no modelo de avaliação multicritério. Para classificar as escolas em categorias de mérito, de acordo com o seu desempenho em múltiplos critérios, utilizou-se o método ELECTRE TRI. O modelo foi desenvolvido e aplicado a um conjunto de oito escolas secundárias, cujos desempenhos foram obtidos no âmbito de um projeto de investigação e desenvolvimento que resultou de uma parceria entre uma empresa de gestão e manutenção de edifícios e três grupos de investigação. O software IRIS permitiu inferir conclusões robustas através da indicação da gama de categorias em que cada escola poderia ser classificada, considerando as preferências do decisor, captadas através dos parâmetros do método ELECTRE TRI.

Os resultados mostram que este processo permite aos decisores aprofundar o seu conhecimento sobre a situação em análise e, eventualmente, adaptar as suas preferências para explorar outros cenários para apoio à tomada de decisões mais informadas relativamente a intervenções nos edifícios para a melhoria do seu desempenho energético.

Palavras-chave

Eficiência energética; desempenho energético; edifícios escolares; métodos de estruturação de problemas; apoio à decisão multicritério.

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List of Acronyms and Abbreviations

AHP	Analytic Hierarchy Process
AHU	Air Handling Unit
AI	Artificial Intelligence
ANP	Analytic Network Process
ARA	Additive Ratio Assessment
BACS	Building Automation and Control System
BEMCS	Building Energy Management and Control Systems
BGC	Bragança
BJA	Beja
BMCS	Building Management and Control Systems
BMS	Building Management Systems
BPIE	Buildings Performance Institute Europe
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
CATWOE	Customers, Actors, Transformation process, Weltanschauung, Owners and Environment
COPRAS	COmplex PRoportional Assessment
DM	Decision Maker
DSS	Decision Support System
EBC	Energy in Buildings and Communities Programme
ELECTRE	Elimination Et Choix Traduisant la Realité
EMS	Energy Management System
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificates
EU	European Union
FBM	Fogg Behaviour Model
FM	Facilities Management
GBTool	Green Building Tool
GHG	Greenhouse Gases
GRD	Guarda
HBI	Human-Building Interaction
HDD	Heating Degree Days
HEI	Higher Education Institution
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
IEQ	Indoor Environmental Quality

IRIS	Interactive Robustness analysis and parameters' Inference for multi-criteria Sorting problem
LEED	Leadership in Energy and Environmental Design
LSB	Lisboa
MACBETH	Measuring Attractiveness by a Categorical Based Evaluation Technique
MCDA	Multi-Criteria Decision Aid
MCDM	Multi-Criteria Decision Method
MMV	Montemor-o-Velho
MTS	Matosinhos
NABERS	National Australian Built Environment Rating System
NZEB	Nearly-Zero Energy Buildings
O&M	Operation and Maintenance
OR	Operational Research
ORME	Office Rating Methodology
OWA	Ordered Weighted Average
PBL	Pombal
PROMETHEE	Preference Ranking Organization for Enrichment Evaluation
PSM	Problem Structuring Methods
PTG	Portalegre
RQ	Research Question
SCA	Strategic Choice Approach
SDG	Sustainable Development Goal
SCE	Sistema de Certificação Energética dos Edifícios
SEforALL	Sustainable Energy for All
SODA	Strategic Options Development and Analysis
SSM	Soft Systems Methodology
TBM	Technical Building Management
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UN	United Nations
USGBC	United States Green Building Council
VFT	Value Focused Thinking
VRV	Variable Refrigerant Volume

Chapter 1 Introduction

This chapter presents an overview of the context and motivation for the work reported in this thesis. A summary of energy performance evaluation is also presented to substantiate the research questions identified. The chapter closes with the thesis outline where each chapter is briefly summarized to guide the reading.

1.1 Context and motivation

Energy plays a major role to achieve prosperity connecting economic growth, social equity, and environmental sustainability, with impact on several sectors (industry, agriculture, services, transport, and buildings). In September 2015, the United Nations (UN) adopted the Sustainable Development Goals (SDG) for 2030 (UN, 2015). It was the first time that energy occupied a central place in the world's development agenda with SDG 7, which aims to "*ensure access to affordable, reliable, sustainable, and modern energy for all.*" The SDG 7 builds on the foundation of the Sustainable Energy for All (SEforALL) initiative, which aims at achieving universal access to modern energy services, doubling the share of renewable energy in the global energy mix and the global rate of improvement in energy efficiency (IEA/World Bank, 2017).

The building sector accounted for the largest share of both global final energy consumption (35%) and energy-related greenhouse gases (GHG) emissions (38%) in 2019 (UN Environment Programme, 2020). In the European Union (EU), buildings also contribute to a large amount of the region's total final energy consumption (40%). Therefore, improving the energy performance of the European building stock constitutes an effective way to alleviate the EU energy imports dependency and meet the ambitious goal of carbon-neutrality by 2050 (European Commission, 2019).

The scope of the work presented in this thesis is focused on evaluating the energy performance of school buildings, as an important component of public service buildings. The research work herein reported is partially based on the experience and the results obtained in the framework of a research and development (R&D) project – 3Es – Energy Efficient Schools. The 3Es Project aimed at performing an energy consumption and indoor environmental quality (IEQ) assessment of the *Secondary School Building Modernisation Programme* which has been carried out in Portugal since 2007 (Gameiro da Silva *et al.*, 2013).

The information about the characteristics of non-domestic building stock is scarce, and in most cases inaccurate, since often it is based on estimates, and it is not up to date. According to the report published by the Buildings Performance Institute Europe (BPIE), in 2011, educational buildings in Europe have the third highest building stock (17%), accounting for 12% of the total energy consumed by the building sector (Laustsen *et al.*, 2011). Another report published in 2016, in the scope of Solar Heating and Cooling Programme from International Energy Agency (IEA), estimated that educational buildings represent a share of 20.8% of total non-domestic buildings floor area, based on data from 18 countries (Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Japan, Latvia, Norway, Poland, Slovakia, Sweden, Switzerland, The Netherlands and United States of America) (Dubois, 2016).

For a proper learning environment, school buildings require optimised indoor environmental conditions, including thermal comfort, indoor air quality, lighting, and a quiet atmosphere. In general, energy consumption increases with indoor environmental quality requirements, which leads to an increase in energy costs of school buildings (Becker, Goldberger and Paciuk, 2007; Hong *et al.*, 2014). Due to high energy costs, schools should manage their buildings taking energy efficiency measures into consideration to reduce operational costs and provide suitable indoor environmental conditions to the occupants (Dimoudi and Kostarela, 2009; Escrivá-Escrivá, 2011).

Energy consumption of school buildings depends on many technical, operational and management factors, and rational use of energy is linked to effective facility management and adequate maintenance (Desideri and Proietti, 2002). An effective energy management methodology is mandatory if actions toward energy efficiency improvement should be implemented. This can be achieved by using management techniques, such as monitoring and targeting consumption, to control energy and cost (BRESCU, 2000). To implement actions that improve buildings energy efficiency, it is necessary that the building operation is associated with an effective energy management methodology, as well as an efficient facilities management (FM) procedure. Moreover, the implementation of any energy management system (EMS) should start with an energy audit (Turner and Doty, 2004), which consists of a detailed examination of the energy usage conditions in an installation – the essential tool that gives managers the information to support decision making on improving energy performance (Thumann and Younger, 2003). Energy audits are not only essential for improving energy efficiency and cost reduction, but also represent a key step in the process of reducing the environmental impacts from buildings, facilities, industrial processes and transport systems (Dall'O', 2013).

Several studies using energy auditing techniques to assess the energy performance of school buildings have been carried out. An energy audit was performed in an educational building in Kuwait, aiming at identifying energy conservation measures. In this work, several energy conservation opportunities were identified across electrical and mechanical systems, resulting in 52% of energy savings (Alajmi, 2012). A detailed electrical energy audit in an educational building was conducted in Saudi Arabia. The resulting recommendations, mostly related to heating, ventilation and air conditioning (HVAC), lighting, thermal insulation and shading devices can reach up to 35.3% in energy savings (Sait, 2013). In a study carried out in an academic building in the United Kingdom, the relation between daily electric load profiles and user occupancy patterns was analysed with aim of optimizing the existing control strategies for improving energy performance (Gul and Patidar, 2015).

Energy audits are a strong driver to improve the knowledge about how energy is consumed within the building and identify energy saving opportunities considering economic and technical issues (Shen, Price and Lu, 2012). Audits also contribute to enhancing energy efficiency in public buildings, supporting decision makers (DM) in project funding enabling the assessment of cost-effective energy saving options and improving the benefit/cost-ratio of energy efficiency projects (Annunziata, Rizzi and Frey, 2014).

In the specific case of schools, it is very important assuring proper indoor climate, because children and teenagers are particularly sensitive to poor indoor environments and stay in school buildings along the major period of their growing up years. Children and teenagers are physically in development and, in comparison to adults, they suffer the consequences of a poor indoor environment earlier, i.e., with shorter periods of exposure (Bellia *et al.*, 2010). Several studies highlight that poor IEQ is a worldwide problem. In the United States of America, the General Accounting Office found more than 15,000 schools suffering from poor IEQ (Schneider, 2002). This problem has also been verified in European countries (Dias Pereira, Cardoso and Gameiro da Silva, 2013). Students and teachers performance under poor IEQ conditions, including low ventilation rates, have been studied (Wargocki and Wyon, 2007; Bakó-Biró *et al.*, 2012; Mishra and Ramgopal, 2015) and a remarkable increase in student absenteeism has been verified as a consequence. The relations between learning, ventilation mode, and other classroom characteristics were investigated with data from a Danish test scheme and two widespread cross-sectional studies examining air quality in 800 Danish classrooms (Toftum *et al.*, 2015). In a recent study performed in nine naturally ventilated primary school classrooms in Greece, ventilation rates and indoor air pollutants have been extensively monitored (Dorizas *et al.*, 2015). Also in Greece, a study was conducted aimed at investigating energy efficiency, thermal environment and indoor air quality in public nursery and elementary school buildings based on field measurements and questionnaires (Theodosiou and Ordoumpozanis, 2008).

In the framework of the 3Es Project, an energy and indoor environment integrated approach was used to assess school buildings in the Portuguese mainland territory (Bernardo *et al.*, 2016). More recently, a study investigated the energy consumption of nine Dutch primary schools, and its relationships with school building characteristics, teacher’s behaviour, and IEQ in classrooms (Zhang and Bluyssen, 2021).

1.2 Evaluating the energy performance of buildings

The most significant amount of energy consumed in buildings is used to provide comfortable indoor environmental conditions to occupants, ensuring thermal comfort (heating or cooling) and indoor air quality (mechanical ventilation). Other typical energy end-uses are lighting, domestic hot water, appliances, and other electrical equipment (refrigerators, office equipment, computers, etc.).

The energy system in a building required to perform the final conversion from delivered energy to useful energy services is presented in Figure 1.1. It is possible to define the two major system boundaries: the building itself that demarcates the limit where outside energy flows (fuels, district heating/cooling, electrical energy, and even direct sunlight) reach the building and the indoor environment where the actual energy services take place (Forsström *et al.*, 2011). Figure 1.1 also depicts outflows of thermal and electrical energy related to the integration of building micro-generation systems into smart grids.

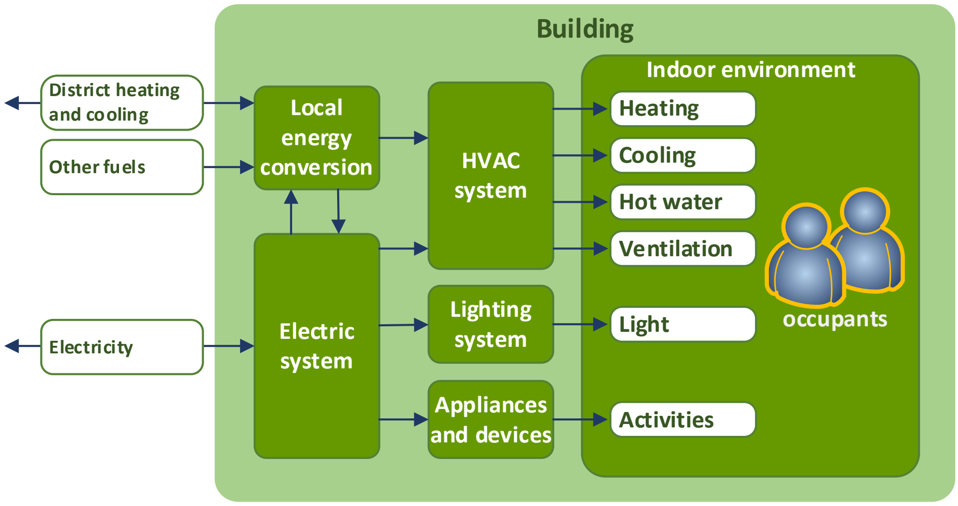

Figure 1.1 – Buildings' systems boundaries - adapted from (Forsström *et al.*, 2011).

In general, occupants demand for end-use energy services to fulfil their needs for indoor environmental comfort. Therefore, the energy efficiency of a building can be defined in a simplified way as the capacity of providing the same services with lower energy consumption or even better services with the same amount of energy (Forsström *et al.*, 2011).

The energy performance of a building is frequently influenced by different types of occupants and stakeholders with different roles, interests, and priorities in what concerns to energy use. Thus, interdisciplinary cooperation among members of research teams is required for energy-efficient building design, coping simultaneously with technological and behavioural issues and their interrelations, thus privileging occupant-centred approaches (Bernardo and Martins, 2020).

The accurate knowledge of the building energy consumption patterns is necessary to make comparative analyses and benchmarking of the actual consumption of individual buildings against others of the same typology using energy performance indicators (Thewes *et al.*, 2014; Sekki, Airaksinen and Saari, 2015). Moreover, this is also useful to find out whether the buildings are complying with energy requirements and being in need of a deeper energy diagnosis (Corgnati, Corrado and Filippi, 2008).

Energy efficiency was firstly introduced in the energy policy agenda of the European integration project in the 1970s as result of the oil embargo and was progressively transformed with the shifting of the global and EU energy and climate policies and priorities (Economidou *et al.*, 2020). The Energy Performance of Buildings Directive (EPBD), introduced in 2002 (European Commission, 2002), its recast in 2010 (European Commission, 2010) and, more recently, its amendment in 2018 (European Commission, 2018), are the key instrument to shape policies and actions to increase the energy performance of buildings in the EU. The EPBD established the mandatory implementation of an Energy Performance Certificates (EPC) framework for buildings across all EU Member States.

The development and effective implementation of an EPC framework is a complex and demanding task, requiring a multi-dimensional approach based on technical, political and socio-economic aspects (BPIE, 2010). In 2014, the EPBD requirements for EPC were formally implemented in all EU-28 Member States national legislation (Figure 1.2).

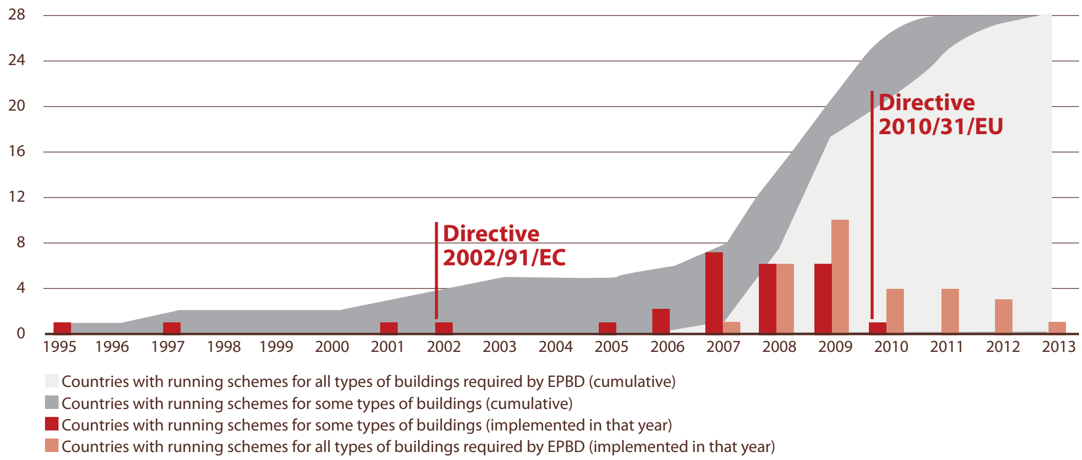

Figure 1.2 – Temporal evolution of EPC systems implementation across EU-28 (Arcipowska *et al.*, 2014).

The EPC registry is adopted, developed, and organized generally at a national level, or, in some countries, at a federal state or regional level. The accessibility and availability of EPC data is very heterogenous across the different EU Member States (Table 1.1).

Table 1.1 – Cumulative number of EPC issued at the end of the years 2011 and 2018, and correspondent percentage change – adapted from (Zangheri *et al.*, 2021).

Country	Non-residential			Public		
	2011	2018	% change	2011	2018	% change
BE-Brussels*	n.a.	n.a.	---	n.a.	307	---
BE-Flanders*	5,408	20,671	282%	6,247	10,511	68%
Bulgaria	553	4,997	804%	n.a.	n.a.	---
Czech Republic	n.a.	9,450	---	n.a.	3,446	---
Denmark	22,383	49,094	119%	n.a.	n.a.	---
Estonia	654	4,009	513%	41	438	968%
Finland	n.a.	11,484	---	n.a.	3,693	---
Germany	n.a.	44,398	---	n.a.	n.a.	---
Greece	2,691	262,523	---	394	4,770	---
Ireland	8,023	54,884	584%	n.a.	n.a.	---
Italy	n.a.	54,402	---	n.a.	2,916	---
Lithuania	406**	2,836**		2,010	13,198	557%
Portugal	21,474	157,299	633%	913	4,376	379%
Slovakia	224	1,237	452%	1,443	6,686	363%
Slovenia	n.a.	2,412	---	n.a.	2,662	---
Spain	n.a.	305,372	---	n.a.	n.a.	---
Scotland	n.a.	6,355	---	n.a.	n.a.	---

*Each federal region of Belgium (Flemish (Flanders), Walloon and Brussels-Capital) has its own EPC legislative body

**including industrial buildings

Despite the information about the adoption rate of EPC is available only for a limited number of countries, the number of EPC issued to non-residential and public buildings has significantly increased between the years 2011 and 2018.

For assigning an energy label, the energy performance of buildings can be evaluated based on the calculated (known as asset rating) or measured energy consumption (known as operational rating). Operational rating is appropriate for existing buildings that are large and complex, including both public and commercial buildings, in which change of users is infrequent and user behaviour is therefore quite stable. Asset rating is appropriate for new buildings, for which measured data do not exist (IEA, 2010).

Nevertheless, EPC labelling assigned to the buildings only reflects energy consumption or GHG emissions (in terms of CO_2 equivalent). This has the advantage of being easily recognizable for building owners and users as it reflects the way energy bills are paid; however, this is more targeted to larger environmental impacts, and is more relevant to governments and wider energy reduction goals. Moreover, many environmental issues related to the building sector could also be assessed (e.g., indoor environmental quality, land and water use, sustainability of materials, waste handling). The use of both life-cycle and broader environmental assessments of buildings has been growing steadily, and various environmental assessment systems for buildings are now in use worldwide (IEA, 2010).

Certification schemes for sustainable buildings or green building rating tools addressing several different environmental impacts at the same time have been developed as a market signal for green building features (to evaluate, improve and promote the buildings' sustainability) (Nguyen and Altan, 2011; Matisoff, Noonan and Mazzolini, 2014). These sustainability certification tools have been conceived as voluntary in their application, but they may lead to financial benefits due to increased building performance and marketability of the buildings, while improving indoor environmental quality (Matisoff, Noonan and Mazzolini, 2014; Gabe and Christensen, 2019).

Some of the most well-known and adopted building qualitative environmental rating schemes are Leadership in Energy and Environmental Design (LEED) in the United States; Building Research Establishment Environmental Assessment Method (BREEAM) in the

United Kingdom; Green Building Tool (GBTool) in Canada; Comprehensive Assessment System for Built Environment Efficiency (CASBEE) in Japan; and the National Australian Built Environment Rating System (NABERS) in Australia. Several assessment schemes have been adapted for use in other countries (Fowler and Rauch, 2006; Silva, 2007; Roderick *et al.*, 2009; IEA, 2010; Nguyen and Altan, 2011; Bernardi *et al.*, 2017).

According to the literature, LEED and BREEAM, which will be briefly described below, are the most comprehensive and the most widely used across the world (Nguyen and Altan, 2011; Lee, 2013; Kudryashova, Genkov and Mo, 2015; Awadh, 2017). The BREEAM system was developed by the Building Research Establishment (BRE), in the United Kingdom. It covers all building types: schools, healthcare buildings, offices, industrial units, amongst others, including variants devoted to the housing sector. The evaluation of a building is made by assigning points or "credits" to each criterion of different categories, such as: Energy, Management, Health and Wellbeing, Transport, Water Consumption and Efficiency, Materials, Waste, Pollution, Land Use and Ecology. A total score is obtained through a weighted sum of the scores for each criterion. The overall building performance is awarded a rating "Pass", "Good", "Very Good", "Excellent" or "Outstanding" based on the score and a star rating from 1 to 5 stars is also provided (BRE, 2019).

The LEED system was designed by the United States Green Building Council (USGBC), addressing specific environmental building related impacts using a whole building environmental performance approach (Fowler and Rauch, 2006). Similarly to the BREEAM, LEED has been updated and evolved as a tool suitable for all building typologies and for all building phases, including new construction, interior fit outs, operations and maintenance, and core and shell (USGBC, 2021a). The evaluation of a building is made by assigning points to each criterion of different categories: Location and Transportation, Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, Innovation, and Regional Priority (USGBC, 2019). Most of the performance-based criteria follow a linear scoring scale. A total score is awarded by adding the points obtained for each criterion. As a condition for earning LEED certification, the applicant project must satisfy all pre-requisites and score a minimum number of points (Lee, 2013). The overall building performance is awarded four possible ratings "Certified", "Silver", "Gold" or "Platinum" based on the total score (USGBC, 2021b).

Despite the contribution of the methodologies and certification schemes described above for increasing the sustainability of the built environment, Ade and Rehm (2020) conducted a study supported by a literature review and interviews with key industry participants named in the paper as the "founding fathers" of the green building rating systems. The study unveiled some of the most common drawbacks and pitfalls in the creation and operation of the rating systems that had failed to transform the market, which are summarized as follows (Ade and Rehm, 2020):

- expensive assessment methodology that increases the construction cost, due to the significant time commitment required, resulting in increased consultant and certification fees;
- designers and owners are driven by scoring points instead of improving the sustainability;
- energy modelling is complex and the process and the certification process is harmed by bureaucracy;
- building performance is measured against an average industry benchmark/building code, rather than against an absolute performance goal;
- the dominant rating tools are predominately focused on new buildings instead of existing buildings;
- the occupants/tenants beahvior impact on the building performance is not considered in the evaluation;
- the main purpose is to indicate to the market what could be the potential performance, instead of alowing informing on the actual, ongoing performance of a building.

An additional issue identified is that the green building rating systems were commonality designed to be implemented by key members of the construction industry with potentially vested interests, such as property developers, architects, construction companies or corporate owners and landlords. These tools were not designed for use by homeowners, tenants or building occupants. Developers typically do not require a rating tool that measures and reports on actual performance as they have either moved onto the next project or sold the building. Indeed, a tool that measures actual performance could potentially be detrimental to them, highlighting that the building may not perform as advertised (Ade and Rehm, 2020).

1.3 Research questions and objectives

To overcome the barriers identified, the main purpose of the research work presented in this thesis is to develop a holistic rating system taking into consideration multiple and, in general, conflicting, and incommensurate aspects that influence energy efficiency in school buildings. This system promotes the involvement of the main stakeholders to support non-experts working in entities that deal with energy management problems, also with impact on IEQ and even far-reaching issues associated with the involvement of the community regarding the dissemination of good practices. The proposed system will have the ability to be updated with new data allowing for the continuing evaluation of the building performance. The perspectives and preferences of the stakeholders and the occupants can also be integrated in the assessment.

Therefore, three main research questions (RQ) were formulated:

- RQ 1. Who are the relevant stakeholders, and which are their roles in the energy management process of schools?
- RQ 2. Which are the most relevant aspects that can have impact on the energy and sustainability performance of school buildings, including non-energy criteria?
- RQ 3. How to design a multi-criteria decision aid system for evaluating the energy and sustainability of school buildings incorporating the different stakeholder's preferences and perspectives?

To achieve the proposed objectives, a multi-criteria classification system considering multiple, conflicting, and incommensurate evaluation aspects influencing energy efficiency in school buildings has been developed. The multi-criteria ELECTRE TRI method is used to classify energy performance of school buildings into categories of merit according to the multiple criteria using the IRIS software. The alternatives under evaluation are assigned to predefined ordered categories according to their absolute performance and not in comparison with the performance of the other alternatives. Each alternative is assessed using reference profiles defining the boundaries of the categories in which the alternatives should be sorted. The model was applied using a set of performance indicators obtained in the framework of the 3Es Project aimed at assessing the energy performance of a sample of Portuguese school buildings. The software IRIS, which implements a version of ELECTRE TRI, allowed for inferring robust conclusions by indicating the range of categories for each alternative, considering the DM's preferences, captured by the parameters of ELECTRE TRI.

1.4 Thesis outline

The thesis is divided into six chapters according to the structure presented in Figure 1.3 and the specific chapter descriptions are as follows:

- Chapter 1 describes the context, motivation, research questions and objectives of the thesis, including a discussion on methods for assessing the energy efficiency and sustainability of buildings, as well as the thesis organization.
- Chapter 2 presents a critical literature review about the relations between occupants and buildings and technology, identifying the main behavioural issues affecting the energy performance of non-residential buildings. The role of building automation and control systems and further aspects related to human-technology interaction are also approached.
- Chapter 3 introduces a background and literature review on multi-criteria decision aid concepts and methods, including: a summary of problem structuring methods, a general discussion on multi-criteria decision aid methods, and a brief description about the use of MCDA approaches to evaluate energy and sustainability issues in buildings.
- Chapter 4 adresses the application of SSM combined with VFT for structuring a multi-criteria energy performance classification model for school buildings considering multiple, conflicting and incommesurate aspects influencing energy

efficiency in schools. The relevant stakeholders, their relations and the description of the fundamental objectives are also presented.

- Chapter 5 presents the selection of the alternatives for evaluation. The specification and description of the quantitative and qualitative data used for parametrization of MCDA model is also presented, including reference profiles, thresholds and criteria-weight constraints used. Finally, a selection of results obtained from the exploration of the model is presented and discussed.
- Chapter 6 summarizes the main contributions of the research and provides the answers to the research questions. To conclude, future research topics are outlined.

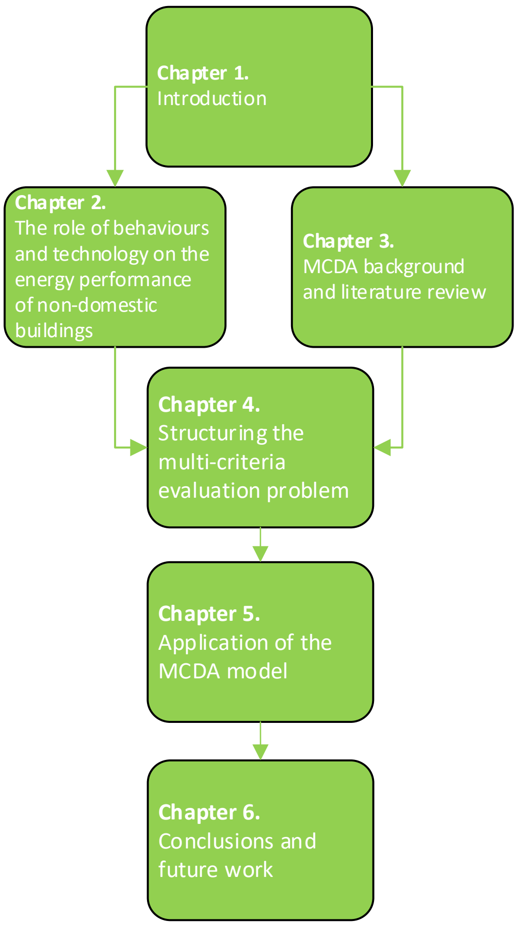

Figure 1.3 – Thesis structure.

Chapter 2 The role of behaviours and technology on the energy performance of non-domestic buildings[1]

This chapter starts by providing the broad context of resource efficiency from the perspective of buildings' life-cycle. It follows with the identification of the main behavioural issues affecting the energy performance of non-residential buildings, which are inextricably connected to the comfort conditions provided to the occupants. The role of building automation and control systems (BACS) which are installed in buildings is also mentioned in Section 2.3, including an application to school buildings. Section 2.4 deals with the requirements of human-technology interaction and the difficulties raised by the absence of user centred approaches at the design phase of buildings and systems. Section 2.5 develops on the user centred perspective of human-building interaction (HBI) in several dimensions. The chapter ends with a section on some possible courses of action concerning the necessary interdisciplinary approach addressing the relations between people and buildings and technology.

2.1 Perspective on the life-cycle path of buildings

The concept of energy neutral building (Thomas and Duffy, 2013) has been specified and disseminated under several forms, including in regulation, in several geographies (California Energy Commission, 2007; European Commission, 2018).

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[1] This chapter is based on the book chapter: Bernardo, H. and Martins, A. G. (2019) 'Chapter 2.1 - Resource-efficient nondomestic buildings: Intertwining behaviour and technology', In: Lopes, M., Antunes, C. H., and Janda, K. B. (eds) Energy and Behaviour: Towards a Low Carbon Future, Academic Press, pp. 109–127.

A variation of this concept consists of the neutral buildings regarding GHG emissions (Sørensen *et al.*, 2017), which represents a step forward compared to the more classical approach to solely improve buildings energy use. In fact, there are several possible ways to reduce energy consumption with different impacts on GHG emissions.

Improving energy performance of buildings corresponds to implementing some changes, either technological or managerial or both, leading to a lower energy consumption while keeping the same comfort level. It mainly addresses the operating phase of the whole life-cycle of a building. The ambition of achieving energy neutrality of a building goes beyond the improvements of energy efficient use. Energy neutrality requires that the efforts towards a better use of energy resources are complemented with the possibility of *in situ* renewable primary energy conversion. This sustainable *in situ* energy supply aims at the satisfaction of the residual energy consumption that remains after ensuring a (near) optimal building energy performance (European Commission, 2018).

It has been shown that the operational phase of a building represents the majority of energy use during the whole life-cycle of the building (Soares *et al.*, 2017). Nevertheless, a cradle to grave approach (Khasreen, Banfill and Menzies, 2009) has been pointed out as the most comprehensive and rational one regarding a sustainable use of resources. All activities preceding construction, the construction itself and the dismantling of a building have significant impacts on the use of energy and other resources that should be taken into consideration as well. Therefore, the Nearly Zero Energy Building (NZEB) concept (European Commission, 2018), virtuous as it can be, is limited in scope. More recently, a broader concept of carbon-neutral building or zero-emissions building has emerged as a response to the climate neutrality goal in the building sector (European Commission, 2021).

Several well-known factors influence the future energy performance of a building since the very early stages up to the end of its life-cycle: location, exposure, orientation, (passive) design, construction, test and commissioning, operation, demolition, re-utilization of components, residues management (Soares *et al.*, 2017).

Each one of these factors, up to the operation phase, has a specific influence on the resulting use of energy until the end of the useful life of the building. The building structure, including its envelope characteristics, together with all the active systems that provide energy services for internal comfort, are the material basis that set the limits to the quality of the building's performance. Examples of such energy services are heating and air conditioning, lighting, internal transportation, and the BACS that controls energy services provision (Tian *et al.*, 2018). The set of physical and technical characteristics of a building defines the limits within which the building occupants' behaviour influences the actual performance of the whole system – the building itself and the equipment.

A more generalized view on the influence of behavioural factors on the building impact on the use of resources should also consider the behaviour of all agents that develop some kind of activity throughout the building's life-cycle, and not only occupants: designers, contractors, construction workers, FM staff, building managers, visitors. The scope of this chapter is limited, though, to the operational phase of buildings and to the role of those agents that have some influence on the building energy performance during this phase, namely occupants, FM staff, building managers.

The importance of the operational phase must be seen from a broader perspective, in both dimensions of space and time. Whatever is learned from systematic data gathering for the characterization of the building operational phase is very important also for the constant improvement of design approaches and methods. This configures an iterative process where design tools lead to increasingly more efficient buildings and, sequentially, these originate new data streams on systems and behaviours which lead to the improvement of design tools. Software simulation platforms, abundantly used for efficient building design, are one example, benefiting from permanent improvements that are possible through data collection on building use (Huang and Niu, 2016). This sequential closed loop process has a potential positive effect on the evolution of the performance quality of buildings: intelligent design for maximizing comfort and minimizing the use of resources, consistent measurement of relevant data towards performance indicators, systematic monitoring of occupants' behaviour, level of satisfaction and quality of the interaction with buildings' systems, research for interpreting the data towards model improvement, updating/reformulation of design assumptions, models and methods, and back to the beginning in an iterative, closed loop path (Tian *et al.*, 2018).

Although the life-cycle assessment of buildings has become a basic model of regulatory mandates in many parts of the world (European Commission, 2018), this chapter is specifically dedicated to the influence of the relation between technology and behaviour on buildings performance, thus deliberately focusing on the buildings' operational phase.

2.2 Main factors affecting the energy performance of non-residential buildings: focus on occupant behavioural issues

There is a considerable difference between the predicted energy consumption of a building at the design stage and the actual measured energy consumption when the building is at “normal” operation and occupancy conditions. The occupant's behaviour and operation control practices are dominant factors for the existence of this difference, which are difficult to predict at the design stage as they depend on several human factors (van Dronkelaar *et al.*, 2016).

There are many situations when building occupants tend to passively accept technologies and building features of their surrounding environment, but some of their comfort needs are required to be met in order to keep them motivated (Haynes, 2008) to an energy efficient behaviour. Otherwise, there is the risk of counterproductive behaviour that may lead to an increase in energy consumption (Xu *et al.*, 2017).

Despite the tolerant behaviour, people have a natural desire to have some degree of control over the surrounding environment, which may have consequences in buildings energy performance. Indoor environmental conditions may trigger occupants to interact with the building control systems, causing changes in energy demand. These adaptive actions undertaken by the occupants may generate a perturbation of the indoor environmental conditions (Hong *et al.*, 2017). Adjusting the comfort temperature set-points, switching lights, opening/closing windows, pulling up/down window blinds, and moving between spaces, can have a significant impact on energy use and IEQ in buildings (IEA-EBC, 2017).

2.2.1 Paths to the diagnosis of behavioural influence on buildings energy performance

In order to guide the design and operation of low-energy buildings, either residential or non-domestic buildings, that integrate technological and human dimensions, it is crucial to understand occupants’ behaviour in a comprehensive way, integrating qualitative approaches with data- and model-driven quantitative approaches, and employing appropriate tools (Hong *et al.*, 2017).

There are several methods to collect occupant-related data for the purpose of characterizing occupants’ behaviour – each with its own strengths and weaknesses. Within the research conducted under the IEA-ECB Annex 66: “Definition and Simulation of Occupant Behaviour in Buildings”, the approaches for monitoring and data gathering occupant behaviour in buildings were summarized as follows (IEA-EBC, 2018):

- ***In situ* monitoring studies**, which involves monitoring occupant’s actions, presence, and IEQ in operating existing buildings; data are normally acquired passively through BACS or dedicated sensors installed for research purposes; typically, data collection is dedicated to long-term studies (months or years);
- **Laboratory experiments**, requiring the construction of artificial environments similar to real ones, but with high degree of control over the indoor conditions and with the possibility to select participants according to pre-defined criteria; it allows for detailed monitoring of occupant´s actions and comfort perceptions under several controlled scenarios;
- **Surveys, interviews, focus groups, and diaries**, where occupants self-report actions, presence, IEQ perception, and other relevant information, either by filling out questionnaires or through interviews and focus groups; this method is used either alone or together with sensor-data gathering;
- **Virtual reality experiments**, using computer-designed environments to study the occupant’s behaviour when exposed to certain type of stimuli; nowadays still limited to the visual and acoustic domains, they do not yet allow to perform thermal comfort and indoor air quality experiments.

Despite the first three methods are the most developed ones, the use of surveys overcomes key barriers to the adoption of state-of-the-art sensing technology, which include high costs for initial installation, operation, and maintenance, and the difficulty of integrating the sensors with existing BACS. In addition, surveys are a valid alternative to behaviour sensing when direct monitoring techniques are not allowed or are insufficient in what concerns the scope of the research being conducted (Hong *et al.*, 2017).

2.2.2 The role of management decisions and middle-out agents in building performance

Non-domestic buildings are used for a diverse range of activities, whether they are schools, hospitals, commercial spaces, etc., all with different management priorities and strategies, sometimes without considering energy cost. In general, there is a lack of awareness on energy performance issues amongst the organizations' top managers who are responsible for decision making. Management decisions play a determinant role in building performance, both from the point of view of investment in technology and of the building operation.

The resulting operation and energy usage profiles depend on the building's operation and maintenance (O&M) practices and schedules, activity, shape, size and age, among other factors, making it difficult to define a typical non-domestic building (Delay, Farmer and Jennings, 2009).

Janda and Parag (2013) proposed the use of an approach based on the action of middle-out agents for improving buildings' energy performance. This strategy is a normative approach which recognizes those actors who are already performing various roles in society and are neither at the top nor at the bottom of an organisation hierarchy. It examines their agency and capacity characteristics (or potential) with reference to the various aspects of change and/or barriers for change, explores the various directions in which they could act (upstream, downstream, side-ways), and assesses ways to empower them in order to enable change to happen (Janda and Parag, 2013; Parag and Janda, 2014).

In the non-residential sector, due to the extension of technical facilities and profusion of technical equipment, there are usually professionals responsible for building operation and FM. These professionals are key intermediaries between the users/occupants of the building and the control of the building's energy services, playing an important role on organisations' energy management strategies (Banks, Fawcett and Redgrove, 2016).

Considering the building operators/facilities managers as middle-out actors in the context of existing school buildings, the middle-out approach could be used as a strategy to initiate, motivate, support and upscale change in the use of technology towards lower energy buildings (Figure 2.1).

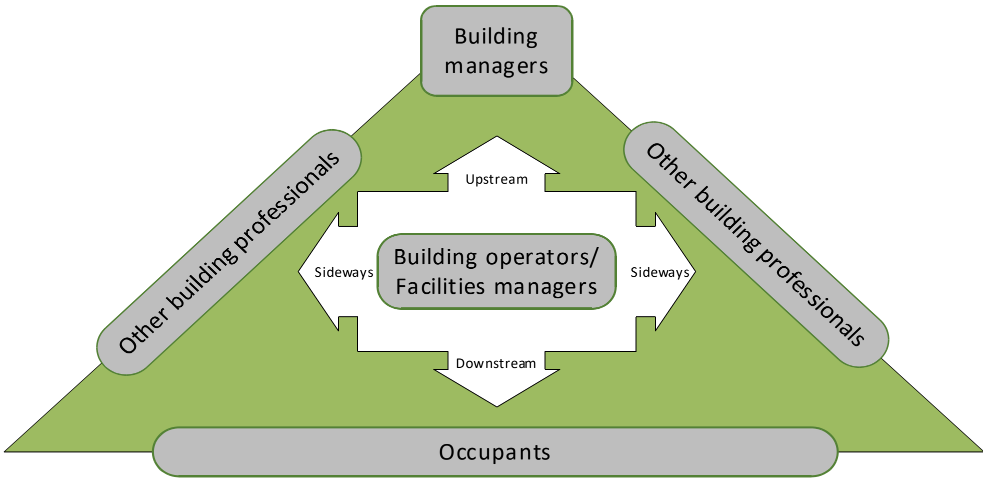

Figure 2.1 – Application of middle-out approach to school buildings - adapted from (Parag and Janda, 2014).

Building operators and facilities managers may have influence on different directions across the building management and operation structure:

- **Upstream:** they can influence the building management to the need of investment in technology, equipment upgrade by means of the procurement of new low-energy technical solutions and supporting the investment decisions; they also play an important role in performing energy accountability and communicating to managers the benefits of an effective energy management strategy;
- **Downstream:** they are crucial agents in meeting the occupants' demand for comfort conditions as they are the intermediaries between occupants and technology, often being the only ones which have permission to change parameters

in the BACS, such as temperature set-points, mechanical ventilation schedules, etc.; they have the responsibility of keeping facilities operation as efficiently as possible, mediating the occupants' comfort needs and management restrictions in terms of reducing the energy cost;

- **Sideways:** innovative FM and energy efficient practices are transferred within building operators and FM professionals, but also to other professionals working in the sector, such as consultants, engineers, amongst others; this could be achieved through networks of formal contracts when they work in multidisciplinary teams, professional affiliation in professional associations, and also by means of informal relations with other building professionals.

On one hand, facilities managers are in a unique position to understand the occupants demand for indoor comfort conditions. On the other hand, they know how systems and building technology work to contribute for the implementation of low energy buildings (Min, Morgenstern and Marjanovic-Halburd, 2016).

Due to the important role played by building operators and facilities managers, they need knowledge and tools to support them on managing and operating technical building systems, maximizing occupant's satisfaction with adequate indoor environmental conditions and low energy use.

2.3 The role of existing building automation and control systems

An important way of saving energy and reducing GHG emissions in non-domestic buildings relies on the use of ever more sophisticated automation systems to monitor and control the active and natural systems providing heating, cooling, lighting, etc. to the building.

Much of the energy used for heating, cooling, ventilation, or lighting in a building may be wasted in periods of low or even zero occupancy while being insufficient in higher occupancy periods. An artificial lighting system may be at once excessive in daylight periods and insufficient without daylight. Some buildings have simultaneous heating and cooling needs (due to solar orientation, etc.) which are provided by nonintegrated/interlocked HVAC systems, increasing the energy needs compared to an integrated system. These are just a few examples to illustrate the potential savings that can be obtained through building automation.

According to EN ISO 16484-2:2004, a BACS is a “system, comprising all products, software and engineering services for automatic controls (including interlocks), monitoring, optimization, for operation, human intervention, and management to achieve energy-efficient, economical, and safe operation of building services”. Some systems known as Building (Energy) Management (and Control) Systems (BMS, BMCS, or BEMCS) fit the BACS definition in EN ISO 16484 and should therefore be designated as BACS. These systems have gained a prominent role in the management of daily maintenance and energy-related operations with significant impact on the energy performance and indoor environmental quality of buildings (Oliveira and Bernardo, 2019).

A BACS can be described as a centralized, automated system that receives and monitors information from the various sensors installed across the building, allowing building facilities managers and operators to control actions based on schedules, inputs from sensors, and preferences expressed by occupants. It can be programmed to control all building energy-related systems, including heating, cooling, ventilation, domestic hot water production, lighting, on-site energy generation, mechanical systems for shading devices, window actuators, double façade elements, and non-energy functions (building security/intrusion detection, fire alarms, etc.). While some of these systems may be very limited (such as only performing system monitoring and data visualization), others may integrate all the building’s systems and include automated control, enabling the automation of various physical tasks that would otherwise have to be performed manually and *in situ* (Brambley *et al.*, 2005).

An important effort to create a standard framework to characterize energy efficiency in these systems was introduced by the European standard EN 15232-1:2017 (CEN, 2017). This standard presents an energy efficiency classification of BACS into four efficiency classes, A to D, based on a structured list of BACS and Technical Building Management (TBM) functions that systems should be able to implement, as well as on minimum requirements for these systems for different building complexities. It also provides standard, simplified methods to estimate and detailed methods to assess the impact on the energy performance of buildings when such systems are introduced, upgraded, or retrofitted.

2.4 Challenges of human-technology interaction

Nowadays, there is still a widespread belief that all energy-related concerns could be overcome by technology despite a progressive awareness of the importance of human behaviour, directly linked to technology usability. On one hand, there are the intentions of technology and control designers and manufacturers, and, on the other hand, there are the users' awareness and perceptions.

Some designers are more influenced by technology manufacturers than by users' needs, corresponding to an expectation that technology-based approaches will be enough to the provision of both comfort and energy efficiency (Bordass, Leaman and Bunn, 2007). Users are not interested in technology itself, but on the results of their interaction with the control systems to achieve comfort. Interactivity between users and technology is provided by the user interface, which desirably allows users to perform adjustments in environmental parameters as simply and quickly as possible – it may be a touchscreen, a thermostat knob, a voice command receiver, a mechanical lever or a switch. If the user interface does not meet some elementary usability requirements, occupants will give up since they cannot achieve what they want quickly and easily (Bordass, Leaman and Bunn, 2007).

Frequently, design purposes do not match user needs and perception of the control functions, tampering the effective and efficient operation of the system. In most cases, this may be due to a lack of communication between technology designers and building owners, operators, and users, contributing to a lack of general awareness about the causes and consequences of poor control and user interface design. Some of the barriers and drawbacks identified are summarized in Table 2.1.

Table 2.1 – Summary of barriers and drawbacks in design, installation, and operation stages, affecting systems' usability on the perspectives of designers and users (Bordass, Leaman and Bunn, 2007).

	Designer	User
Design	Design reality may not match practical reality: - Lack of good specifications for usability. - Poor feed-forward of supplier experience.	Poor understanding and discussion on user experience: - Building owners do not realise the importance of user interfaces. - Narrow engagement of building owners in setting the user interface requirements.
Installation	Design intent becomes blurred during implementation: - Lack of products with adequate usability requirements. - Insights lost down the supply chain. - Fine details (location and labelling) are poor.	Actuality drifts away from client expectation during implementation: - Detailed provisions not discussed with building owners and users. - Management not involved in agreeing details. - Handover procedures and data are often poor.
Operation	Management gets involved when it does not need to be. Lack of feedback on in-use performance.	Users experience both intended and unintended consequences. Design intent and system response often unclear to user.
All phases	Lack of feedback to controls manufacturers.	

There are cases of buildings provided with a large range of control functions, which are operated using only few of them, mainly due a lack of knowledge and empowerment of the building's operators and facilities managers (Bernardo, Martins and Gaspar, 2013; Paone and Bacher, 2018). Figure 2.2 provides some insights into the general range of available BACS functionality and the degree to which buildings' operators exploit the available functions. The information presented was collected through interviews to building operators conducted in eight school buildings in Portugal.

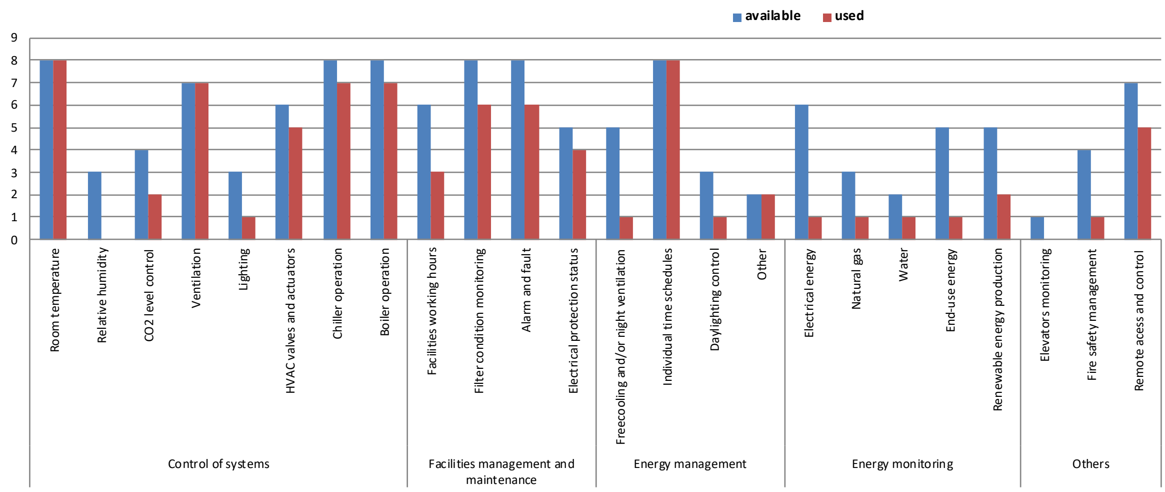

Figure 2.2 – Surveyed prevalence and utilization rates of selected BACS functions (Y-axis displays the number of occurrences).

It is patent that most BACS are used to perform basic plant control functions. However, many BACS have a certain number of more sophisticated functions, such as daylight control, free-cooling (night-cooling) or demand control ventilation. The results of this survey clearly support the argument that many BACS do not make use of a significant portion of their potential functionalities. Other studies also state that building operators tend to use only a fraction of possible BACS functionalities, thus limiting the performance gains, and also that in many buildings the system does not operate correctly (Lowry, 1996, 2002). During the interviews conducted in Portuguese schools, it was found that only one building operator had previous experience and knowledge on the use of BACS, and only half of them had initial training for operating the system when starting their professional activity related to building O&M.

Another factor that usually affects the BACS performance is the non-existence of a stage of system commissioning or a poorly conducted commissioning. This stage plays an important role in building performance since it is required to ensure that the building equipment and systems are integrated in such a way that they perform together effectively and efficiently and meet the building operation management requirements and expectations (Aghemo, Blaso and Pellegrino, 2014).

Technology also faces some challenges to integrate future energy-related issues, such as shifting to a demand-control paradigm where the technical building services should have the capability of automatically adjusting energy demand to follow actual occupancy profiles, instead of operating at full load to meet pre-defined standards or peak occupancy profiles.

In the context of smart grids, the automation and control systems must have the capability to deal with and to optimize, in an integrated way, the use of renewable energy sources, electric vehicles, energy storage and demand response actions (Carr *et al.*, 2017).

2.5 Human-building interaction

HBI deals with the ways through which the occupants of a building interact with it, its components, and its technical systems, as well as the influence of the behaviour of occupants in the overall building energy performance. The aim of this study domain is not only identifying the factors that influence behaviours but, under a generalized perspective, assessing how to influence behaviours in such a way that building energy performance can be maximized while preserving or improving occupants' comfort (Shen *et al.*, 2016).

Occupants are therefore agents of adaptation of local internal comfort, in a setting where immersion into the interactive object itself is a singular characteristic of HBI (Nembrini and Lalanne, 2017). They act on their surroundings to influence building response, which causes changes in energy consumption and consequently affects building performance (Delzendeh *et al.*, 2017).

The assumptions made about occupants' behaviours in the context of software tools for assessing the energy performance of buildings are usually simplified, based on rational decisions of occupants, or simply neglecting the role of occupants on the use of the building or its technical systems. In many cases, assumptions are made only on the number of occupants for the sake of identifying the influence of biological internal gains on the building's thermal load. This inevitably leads to estimations on energy use which are far from being coincident with reality when comparing simulations with measured data. The difference between these values is usually designated energy gap (Delzendeh *et al.*, 2017; IEA-EBC, 2018; Paone and Bacher, 2018).

The energy gap is the target of many research initiatives which aim at improving the capacity of software tools to identify more accurately the actual performance of buildings. This is a key issue either when designing new buildings, when renovating existing buildings, when performing post-occupancy evaluations of existing buildings, or even when energy audits are accompanied by energy performance simulation to test or fine tune energy efficiency measures to be adopted (Robinson, Foxon and Taylor, 2016; Hong *et al.*, 2017).

It has been shown that building occupants assign a very high value to the capacity of influencing their surrounding environment through acting, for example, on windows, shades, lights, or thermostats, towards their perceived comfort, not necessarily towards an efficient use of energy. Comfort affects productivity and, ultimately, occupants' health, which must be considered not only in business management decisions but, in the first place, in the design of spaces and their functionality. Too many constraints, or too intense attempts of persuasion, to influence occupants' behaviour usually lead to high levels of rejection and are counterproductive (D'Oca *et al.*, 2018).

2.5.1 HBI and highly efficient buildings

Buildings which have been conceived as potentially highly efficient usually require adequate instructions and training of occupants along with appropriate feedback mechanisms that ensure a smooth adaptation of users to the building's characteristics, devices and technical systems (Hauge, Thomsen and Berker, 2011). This is due to the operational features of these types of buildings, which are usually different, in one way or the other, from the commonly designated conventional buildings.

Highly efficient buildings can provide high levels of comfort to occupants with a modest energy consumption. A high energy intensity does not necessarily mean a high comfort level. The main requisite for a convenient adaptation of occupants to an energy efficient building lies in the design phase, when a user-centred approach should be adopted for the best results, i.e., providing comfort and allowing for easy adaptation actions of occupants with minimum energy consumption. Post-occupancy adaptation of existing buildings should follow a similar path for the best results (Steemers and Manchanda, 2010).

The particular demands posed by energy efficient buildings towards an optimum use of resources, including water, for example, are frequently causes of rejection by occupants, who develop a negative attitude towards these demands (Ornetzeder, Wicher and Suschek-Berger, 2016). In fact, in many cases, in the absence of training and meaningful feedback, together with overly complex operational requirements caused by a non-user-centred approach, occupants feel incapable of developing adaptation strategies that allow them to obtain the comfort conditions they aim at (Hauge, Thomsen and Berker, 2011; Shen *et al.*, 2016). These cases, although technologically efficient, hardly, if ever, lead to an energy efficient operation of buildings and actually correspond to a poorly designed HBI (Leaman and Bordass, 1997).

2.5.2 User-centred HBI

A user-centred design must address all levels of HBI requirements: the building itself, including all the non-static components, that may be influenced by user actions, technical systems - those which provide essential energy services towards visual and thermal comfort, as well as air quality, control systems and O&M. The main features of a user centred HBI design are:

- **simplicity of use:** interfaces should be intuitive, with a smooth and short learning path, under the principle of making things easy and avoiding any expendable complexity for the purpose sought, which should be to make occupants feel comfortable with minimum adaptation action; this, in turn, makes the building operate as near as possible to the expected operational conditions, that is, an energy efficient operation;
- **ergonomics**, which is closely related to simplicity, essentially ensuring ease of use;
- **eco-feedback**, to provide appropriately persuasive stimuli trough co-design and co-creation with users whenever possible.

The temptation to avoid appropriate HBI requirements through extensive automation aiming at a total and unquestioned satisfaction of users is usually doomed to failure, leading to the standard user rejection effect (Paone and Bacher, 2018).

D'Oca et al. (2018) illustrates the influence of simplicity with the results of a comparative study that showed small office buildings to have a better energy performance than large office buildings, having in mind that small buildings were almost exclusively manually operated, with simple to use devices.

Plug loads are a specific type of load in the sense that they are not prone to automatic control. Therefore, they require innovative HBI solutions, which creatively integrate elements such as suggestive feedback, comparison, emulation and awareness raising, to contribute to an efficient use of energy in office buildings, where space and labour organization have a strong influence (Metzger, Kandt and VanGeet, 2011).

The most common types of devices and the most common types of actions performed by occupants on those devices are the subject of ongoing research to suitably integrate their influence on energy consumption of buildings in the context of simulation software packages. Sociology plays an important role in this research in the scope of interdisciplinary teams, to identify and interpret the influence of specific barriers, stimuli and incentives, the importance of contextual issues or the influence of the variety of occupants' profiles, bearing in mind that the behaviour of an individual person may also vary with acquired experience of building use (D'Oca *et al.*, 2018).

Shen et al. (2016) used the Fogg Behaviour Model (FBM) (Fogg, 2009) to devise a strategy for influencing occupant behaviour in a commercial building, dealing with the need to reduce energy consumption of office plug loads. In FBM there are three basic elements for persuasion: motivation, ability, and triggers. The ability of a person to perform a certain action depends on the simplicity of that action, which emphasizes the need to ensure simplicity of HBI mechanisms by design. Motivation can be stimulated, leading to an increase of the motivation level, an example of which may be the above-mentioned eco-feedback, among several others. A trigger is a stimulus that defines the moment when the action is taken. It may have a double nature if, for example, it simultaneously contributes to raise motivation, or if it also turns the simplicity of the action evident to the target person. Or it may just be a reminder when motivation and ability are already sufficient.

2.5.3 Building Automation and Control System

BACS, where they exist, are an intrinsic part of HBI. From a rationality standpoint, BACS play a very important role in buildings in general, and specifically in energy efficient buildings. In principle, the existence of a BACS allows for a potentially optimal use of energy in a building designed to be passively efficient and equipped with highly efficient devices delivering the energy services needed for internal comfort. Thus, the automation of energy services provision potentially eliminates the influence of human decisions based on imprecise reasoning or less rational behaviours. The same can be said about not so efficiently buildings (Bordass, Cohen and Field, 2004). The overall result will be less interesting than in the case of highly efficient buildings but, in the context of the existing physical constraints, the results would also be optimal.

However, BACS are not a panacea for efficient use of energy. On a less bright perspective, they add complexity to the building systems, they require maintenance and regular updates, as well as specialized personnel to operate with them (Leaman, Stevenson and Bordass, 2010). Besides, BACS also play an important role in HBI, with all the consequences, positive or negative, depending on specifications and operations (Martins, 1988).

Plug loads are, by definition, not prone to automatic control. Therefore, they constitute a special category which must be tackled carefully, considering all the eligible behavioural aspects. However, the possibility of automating the control of the other types of loads does not ensure per se an optimum operation of a building. Operational BACS problems have long been reported in the literature (Andrews, 1982; Martins, 1988; Ardehali and Smith, 2002). Some of these problems are directly connected to HBI aspects, namely those related to interface and feedback channels to operators and users.

Poorly conceived control strategies, hard to understand interface devices, absence of manual override options provided to users, are some of the problems classically identified in BACS. These types of problems, although identified a long time ago, are presently being researched also from the point of view of the behavioural response of occupants, aiming at improving control strategies and interfaces towards a better acceptance by users and a consequent more efficient building operation. The natural trend of building occupants towards adapting their closest environment to obtain a more comfortable situation, when in the context of a rejected BACS, usually leads to an inefficient operation of the building, inverting the expected positive results of the use of a BACS. Leaman and Bordass (1997) align a systematic view of causes for BACS rejection by occupants, partially organized on an energy service basis, along with possible remedies.

2.5.4 Operation and maintenance

The building as a physical system, as well as the whole set of technical systems and the BACS, all require regular O&M. FM personnel, when available, either part of the building staff or under contract, as stated before, can play a relevant role as middle-out agents, influencing both management decisions and occupants' attitudes towards an efficient use of energy. Occupants tend to appreciate positively the actions of FM personnel when these implement a systematic workplan including interaction with building occupants on good practices (Ornetzeder, Wicher and Suschek-Berger, 2016). This workplan not only corresponds to the component of awareness raising that any coherent program for influencing behaviour should have, but also ensures an effective use of the available HBI mechanisms by the occupants.

In those cases where O&M is not effective, the inevitable degradation of the response of the building and its technical systems contributes to some degree of dissatisfaction, since occupants are no longer able to adapt the operating conditions of their surrounding spaces to their convenience (Leaman, Stevenson and Bordass, 2010). In the worst case, some technical systems may eventually cease to provide energy services, reducing energy consumption at the cost of degrading productivity. In other cases, occupants' actions through a defective HBI usually tend to increase energy consumption without achieving adequate comfort (Paone and Bacher, 2018).

The rejection behaviour of uncomfortable occupants may be potentiated by the actions of a BACS that does not respond to comfort requirements. Improper settings of control parameters or unplanned modifications of some circuitry or software components are likely to happen even if O&M is apparently being performed (Stevenson and Williams, 2007), in the case of external personnel under contract who may not be familiar enough with the system design and operation.

2.5.5 A holistic view of HBI

The increasing penetration of artificial intelligence (AI), mechatronics and robotics in the building environment, together with innovations in the field of sensors and new materials, as well as the use of augmented reality techniques for architectural design support, have been contributing to the emergence of a new perspective on HBI (Alavi, Churchill and Lalanne, 2017). This new perspective goes beyond the objective of increasing energy efficiency, acknowledging the growing importance of embedded interactive technologies in the built environment, to rethink the relation of buildings with their occupants by taking advantage of computing power and new interaction techniques, such as self-adaptive systems and devices that can automatically adjust the response of technical systems to comfort requirements. Although the energy efficiency perspective remains as an essential ingredient, the adaptation of ambient conditions by occupants, intrinsic to HBI, addresses all aspects of subjective well-being and comfort perception, even if not directly related to energy use. This emergent perspective requires a multidisciplinary approach gathering architects and interaction designers. It "address[es] the physical, spatial, and social opportunities and challenges that emerge as built environments become increasingly interactive" as well as collateral issues such as privacy, cybersecurity or technology obsolescence (Alavi *et al.*, 2016).

The increasing sophistication of the built environment assumed in this perspective raises again the question of the legibility (simplicity) of HBI to both occupants and FM personnel, which is key to a seamless adaptation of these agents towards an efficient use of energy (Leaman and Bordass, 1997).

In addition, since a great number of installed BACS in existing buildings operate in conditions which are far from optimal, the need of post-occupancy interventions arise, aiming at a more effective HBI if a large-scale result is sought (Delzendeh *et al.*, 2017).

The most recent version of the EPBD (European Commission, 2018) is oriented to the promotion of building automation, introducing the concept of "smart readiness" as a means of quantifying the ability to improve HBI through BACS dissemination. This policy trend towards profiting the most from technology progress must be informed by accumulated knowledge on the best HBI practices in relation to human behaviour.

2.6 Concluding remarks

There is clear evidence of the intimate relation between technology and occupants' behaviour on the energy performance of buildings. From a life-cycle perspective, an efficient building has the potential to have a much smaller impact on the environment than a building designed and built without a life-cycle perspective. Technology, though, is not enough to achieve that full potential, since the actions of occupants determine, to a great extent, how a building will perform during the operating phase of its life-cycle, which is the phase with the greatest impact.

Occupants of non-domestic buildings tend to try to adapt their local environment to obtain the highest possible perception of comfort, which turns out to be an essential pre-condition to labour productivity. Therefore, building design, including internal layout, building components and technical systems, should be achieved using an occupant's centred approach. This means, for example, that occupants should be able to easily apprehend the requirements of operating their closest environment, for which purpose the interfaces should have adequate readability and provide flexibility of operation while ensuring minimum use of resources, namely energy.

A user centred approach is also a requirement for the operating phase of buildings, where FM personnel, as middle-out agents, may be the connecting link between occupants and their working environments. They keep systems operational, guide or influence occupants' actions and, ultimately, avoid reactions of occupants towards what these could perceive as aggressive or not responsive environments. Simultaneously, these agents may influence the managers' decisions to overcome organisational barriers to efficient use of resources within a building.

The difficulty of quantifying the effects of occupants' behaviours usually leads to a gap between the energy consumption of buildings predicted through computer simulators and the actual values. There is active research on data collection in real environments, which aims at grasping behavioural effects towards the improvement of computer simulators.

BACS are an essential part of efficient buildings in the sense that they leave to occupants only those roles that cannot or should not be automated. Again, a user centred approach is required to provide comfort and avoid waste, simultaneously providing a friendly dialogue with occupants' requirements and actions.

HBI is evolving to more elaborate forms of relation between occupants and buildings. It is supported by emergent technologies, seeking to go beyond the rational compromise between comfort and energy efficiency. It aims at responding to new expectations and demands of humans in a developed society, also addressing issues such as privacy or cybersecurity.

Chapter 3 Multi-criteria decision aid - background and literature review

This chapter presents the main concepts and methods for structuring complex problems to be then analysed using multi-criteria methods. An overview on Multi-criteria Decision Aid (MCDA) is also presented, with emphasis on the method adopted in the context of the present thesis. Afterwards, a review about the use of MCDA in problems related to energy and buildings is described. The aim is not to give detailed descriptions of different methodologies or mathematical formulations, but to provide a conceptual background to the work herein presented.

3.1 Introduction

Decision aid is the activity of using explicit, but not necessarily completely formalised, models to support DM acting according to their values and preferences. The decision support is multi-criteria when there are inherently different points of view resulting in multiple criteria to evaluate the merits of potential alternatives (courses of action) instead of using a single criterion, in general an economic indicator, to depict all the aspects of the problem. It should be noted that under the common designation of multiple criteria approaches, two distinct branches appear in the specialized literature:

- methods for decision support with multiple criteria (or attributes);
- methods for decision support with multiple objectives.

The first designation generally refers to methods devoted to the selection, ranking or categorization of a finite set of alternatives, which are explicitly known *a priori*, i.e., before the application of the method (not necessarily before the study begins).The second designation is concerned with problems in which the alternatives are implicitly defined by a set of constraints in a mathematical optimization model.

Several mathematical model-based decisions are made considering a single maximizing or minimizing objective (optimization paradigm). However, single criterion approaches can mask different underlying perspectives or points of view about the decision context. Such perspectives are thus converted into monetary valuations, or cost-benefit ratios. However, converting environmental or social dimensions to monetary units is controversial and sometimes impracticable (DCLG, 2009).

Adopting a multi-criteria approach has a beneficial role in the decision processes. There are three main advantages in using a multi-criteria approach (Bouyssou, 1993). Firstly, this leads to discussions between the relevant stakeholders to elicit the different points of view, contributing also to enhance the results acceptance. Secondly, it allows to define how to measure and incorporate the uncertainty in the decision context, improving the transparency of the process. Lastly and the most important advantage of adopting a multi-criteria approach is the way of achieving consensus when there are incommensurate and, in general, conflicting evaluation aspects.

The term MCDA (multi-criteria decision aid or multi-criteria decision analysis) is used with the purpose of developing a conceptual and operational framework for supporting decision making (Belton and Stewart, 2002). MCDA was described by Belton & Stewart (2002) as a process that starts with the identification and structuring of a problem, followed by the construction of the model, and finally using the multi-criteria method that best fits the model. The assessment of the potential courses of action (alternatives) is made to inform and challenge thinking, with the final aim of determining an action plan and achieve robust conclusions.

An important issue at the structuring stage to be taken in consideration when choosing the MCDA method is the typology or category of the decision problem to be tackled (Roy and Bouyssou, 1993):

- **description:** the purpose of the analysis is to describe the decision situation in a formal language, in terms of actions, criteria and evaluations, to gain a larger understanding about the problem;
- **choice:** the purpose of the analysis is to select one action (or reducing a set of actions to a smaller sub-set of actions for further analysis);

- **ranking:** the purpose of the analysis is to rank actions according to some sort of preference order, from the most preferred to the least preferred one, eventually accepting *ex-aequo* actions;
- **sorting:** the purpose of the analysis is to assign actions to predefined categories or classes of merit.

The boundary between the types of decision problems is sometimes fuzzy and often a certain level of hierarchy among them is required. For instance, the first outcome of a decision process is the "ranking" of the actions followed by the choice of the "best" action (Cajot, 2018). The selection and ranking problems make comparisons between the alternatives' performances. In the sorting problems each action is evaluated against reference profiles in terms of its absolute merit.

In the present work, the option was for modelling the problem as a sorting problem to evaluate each school building according to its absolute performance regarding reference profiles and not in comparison with the performance of other schools. The energy performance of school buildings is classified into predefined ordered categories of merit, which enables, for instance, the prioritization for funding allocation concerning energy efficiency improvement. The following subsections present the most relevant aspects associated with the structuring of decision problems and MCDA methods.

3.2 Soft OR and problem structuring methods

Operational Research (OR) models and methods aim at helping DM with complex decisions, where the possible courses of action can be implicitly defined by a set of constraints in a mathematical model or explicitly known at the outset. The merit of the feasible solutions is assessed by single or multiple objective functions in multi-objective mathematical models or criteria in MCDA. When multiple, conflicting, and incommensurate criteria are at stake, the incorporation of the stakeholders' values and preferences in the decision support process is required.

Unstructured or ill-defined problematic situations generally involve stakeholders with potentially incommensurable and/or conflicting values or interests, a lack of reliable data, disagreement about the nature of the problem and yet the need for agreement and commitment from stakeholders (Rosenhead and Mingers, 2001; Mingers, 2011).

Over the last forty years, new methods and methodologies have been developed to deal with this type of problems. Those methods are not mathematical, but they are nevertheless structured and rigorous. They are based on qualitative and often diagrammatic modelling procedures. Together, these methods form what is known as Soft OR or Problem Structuring Methods (PSM) (Mingers, 2011).

Soft OR approaches aim to help groups of stakeholders gaining a better understanding of a problematic situation of common interest, which is generally characterized by high levels of complexity, uncertainty, and conflict. This is achieved through modelling and facilitation that enable participants to increase their knowledge about the situation with a view to generate consensus on the problem structure, and usually on initial commitments for potential solutions. In order to achieve this main purpose, PSM must: enable several alternative perspectives to be brought into discussion; be cognitively accessible to actors with a range of backgrounds and without specialized training, so that the developing representation can inform a participative process of problem structuring; operate iteratively, so that the problem representation adjusts to reflect the state and stage of discussion among the actors, and vice versa; allow for partial or local improvements to be identified and committed to, rather than requiring a global solution, which would imply a merging of the various interests.

Several PSM have been proposed in the literature to deal with unstructured and complex problematic situations. Rosenhead summarized a set of PSM in a reference textbook in the field (Rosenhead, 1989; Rosenhead and Mingers, 2001). The main features of the key methods and models can be briefly summarized as follows (Mingers and Rosenhead, 2004):

- **Strategic options development and analysis (SODA)** is a general problem identification method that uses cognitive mapping as a modelling device for eliciting and recording individuals' views of a problematic situation. The merged individual cognitive maps (or a joint map developed within a workshop session) provide the framework for group discussions, and a facilitator guides participants towards commitment to a portfolio of actions.

- **Soft systems methodology (SSM)** is a general method for system redesign. Participants build ideal-type conceptual models, one for each relevant "world view", and compare them with perceptions of the existing system to generate debate about what changes are culturally feasible and systemically desirable.
- **Strategic choice approach (SCA)** is a planning approach centred on managing uncertainty in strategic situations. Facilitators assist participants to model the interrelations of decision areas. The interactive comparison of alternative decision schemes helps them to bring out key uncertainties. On this basis, the group identifies priority areas for partial commitment, and designs explorations and contingency plans.
- **Robustness analysis** is an approach that focuses on maintaining useful flexibility under uncertainty. In an interactive process, participants and analysts assess both the compatibility of alternative initial commitments with possible future configurations of the system being planned and the performance of each configuration in feasible future environments. This enables them to compare the flexibility maintained by alternative initial commitments.
- **Drama theory** draws on two earlier approaches, metagames and hypergames. It is an interactive method of analysing co-operation and conflict among multiple actors. A model is built from perceptions of the options available to the various actors, and how they are rated. Drama theory looks for the "dilemmas" presented to the actors within this model of the problematic situation. Each dilemma is a change point, tending to cause an actor to feel specific emotions and to produce rational arguments by which the model itself is redefined. When and only when such successive redefinitions have eliminated all dilemmas is the actors' joint problem fully resolved. Analysts commonly work with one of the parties, helping it to be more effective in the rational-emotional process of dramatic resolution.

Besides the PSM presented above there are other approaches, such as: Scenario Planning/Analysis, Casual Mapping, Theory of Constraints, Cost-Benefit Analysis, Viable

Systems Model, System Dynamics, and Decision Conferencing (Mingers and Rosenhead, 2004).

The choice for using SSM in the problem structuring process to develop a decision support tool for assessing energy performance of school buildings was due to author's familiarity with systems language in face of his background on engineering and control systems. Within the context of decision-making processes, SSM was also used as a starting point to problem structuring for developing MCDA models (Daellenbach, 1997; Belton and Stewart, 2010).

3.3 A brief description of SSM

SSM was developed by Peter Checkland in the late 1970s at the University of Lancaster, in the United Kingdom. The main purpose of the methodology is to tackle problematic, messy situations of all kinds including social, political, and human issues. It is based on a systems thinking approach as an alternative to the conventional natural sciences experimental method (Checkland, 1981). The basis for its development was the Systems Engineering approach, which was modified (and enriched) in the light of and in direct response to real-life experiences (Checkland and Poulter, 2010). SSM represents a different epistemology with respect to usual systems engineering, in that it is claimed that the system should not be viewed as some part of the world which is to be engineered or optimized. The system should be seen as a process of enquiry in which the notion of a system is no longer applied to the world, but to the process of dealing with the world (Mingers and White, 2010).

The SSM approach consists in an inquiry process with seven stages (Figure 3.1), which leads to a learning and understanding system of the problematic situation under study (Checkland, 1981, 1989).

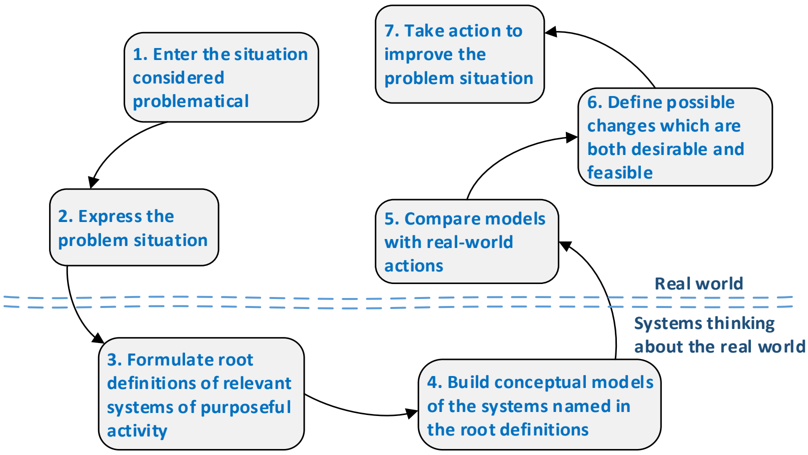

Figure 3.1 – Soft systems methodology overview (Checkland, 1989).

In this process, there are five stages associated with the so called "real-world", two of them for understanding and defining the problematic situation, and the other three for deriving change recommendations and taking actions to improve the problematic situation, based on a comparison of models and real world. There are also two stages related to systems thinking, in which root definitions and conceptual models of the systems are developed.

SSM has gradually undergone some changes and adaptations resulting from several applications by a wide range of groups in different countries. The seven stage process is still presented, but reducing the restrictions to the definition of stage boundaries and including some social and political analysis for a more flexible SSM: the two streams model (Checkland, 1989). In this formulation, there are two parallel sequences, one based on a logic-based stream of analysis through the formulation of activity models according to the seven-stage model. There is also a cultural and political stream enabling judgments to be made about the commitments between conflicting interests, which might be reachable by the stakeholders concerned and would enable action to be taken.

The straightforward progress from stage 1 to stage 7 is not necessarily the way in which SSM should be applied. As long as the logical connections between the stages are kept in mind, the actual problem solving activity can move flexibly between them (Checkland, 1989). An updated description of SSM is given below based on the experience of the worldwide application to several situations (Checkland and Scholes, 1990). This formulation (Figure 3.2) is the one normally used and defines SSM only based on four main activities (Checkland, 2000):

1. Finding out about a problematic situation, including cultural and political issues;
2. Formulating relevant purposeful activity models;
3. Debating the situation using the models, seeking from that debate both:
   a) changes which would improve the situation and are regarded as desirable and (culturally) feasible, and
   b) the commitments between conflicting interests, which enable action to improve to be taken.
4. Taking action in the situation to foster its improvement.

The sequence of the activities is flexible, mainly in what concerns to start and end points and some iterations are common during its definition. Figure 3.2 outlines the cyclic nature of the methodology.

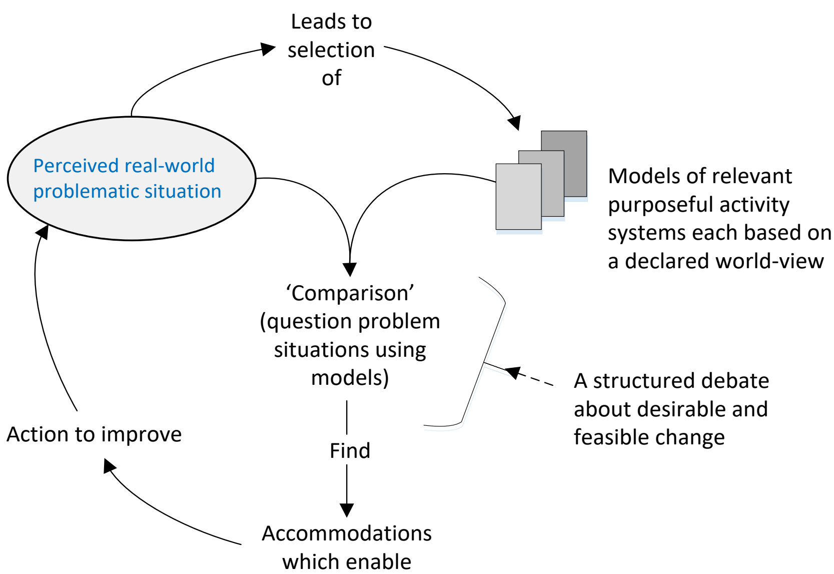

Figure 3.2 – The inquiring/learning cycle of SSM (Checkland, 2000).

One of the reasons why Figure 3.2 is considered to be a better representation of SSM than Figure 3.1 is that the finding out about the problematic situation is apparently lost in "stages 1 and 2", but the finding out continues throughout a study, right up to its end.

3.3.1 Finding out about a problematic situation

The implementation of SSM to a problematic situation requires collecting as much data as possible about the situation to make its representation. Checkland and Poulter (2010) refer that four ways of finding out about a problematic situation have survived many tests and become a normal part of using SSM. In the language of SSM they are known as "making Rich Pictures" and carrying out three kinds of inquiry, known as "Analyses 1, 2 and 3".

Drawing a rich picture to represent the elements in the problematic situation is one of the most widely known devices of SSM. Its purpose is to represent visually the main features of a problematic situation, such as the structures, processes, stakeholders, relationships, culture, conflicts, issues, etc. According to Checkland (2000), its rationale lies in the fact that the complexity of human affairs is always a complexity of multiple interacting relationships, and pictures are a better medium than linear prose for expressing relationships.

The drawings produced are very useful because they can show many pieces of information in a very simplified way and be used to foster discussion. The rich picture enables to elicit comments to improve it and hence the holistic view of the situation, which also contributes to understanding its social and cultural features.

In addition to making a rich picture, other frameworks helping to grasp the problematic situation are provided by Analyses 1, 2 and 3 (Checkland, 1981; Checkland and Scholes, 1990; Checkland and Poulter, 2010). These analyses focus, respectively, on the intervention itself, a social analysis, and a political analysis.

Analysis 1 is the first step to define how to apply SSM to a given situation, identifying the different stakeholders and their roles. It consists of finding out about the situation and requires the identification of the person(s) who will benefit from the analysis ("client"), the person(s) that will conduct the investigation ("practitioners") and who could be regarded as being concerned about or affected by the situation and the outcome ("issue owners").

Analysis 2 consists in understanding the socio-cultural dynamics of the problematic situation and its organizational context in what concerns to social roles, behaviour norms and human emotional values. This is important to improve the situation through culturally feasible changes.

Analysis 3 aims to identify the power relations of the stakeholders involved in the situation under analysis. Particularly, it is analysed how power is expressed and who uses it to accommodate different interests and implement culturally feasible changes. This stage is strongly connected with Analysis 2 to complete a social and political analysis of the investigation context.

The finding out about the situation continues throughout the study, right up to its end and should never be seen as a preliminary task to complete in the beginning of the problem structuring process.

3.3.2 Formulating relevant activity models

The purposeful activity models used in SSM are intellectual devices whose role is to help structure an exploration of the problematic situation. They are accounts of concepts of pure purposeful activity, based on declared worldviews, which can be used to stimulate questions in debate about the real situation and the desirable changes to it. They are simply devices to stimulate, feed and structure that debate (Checkland, 2000). The task is to construct a model of a purposeful "activity system" viewed through the perspective of a pure, declared worldview, one which has been identified as relevant to the investigation (Checkland and Poulter, 2010).

At this stage, it is required that all relevant activities of the problematic situation are clearly defined and understood. After the problem definition and representation, the practitioner enters the "systems thinking world" and generates root definitions of systems that are relevant to the problematic themes that have been identified.

A root definition is essentially a sentence that describes, in an abstract way, the fundamental nature of a system when viewed from a particular viewpoint, as a transformation process. Any relevant activity can be expressed in this form, in which an entity, the input, can be transformed or changed, into a different state or form, as an output of the process. Accompanying the transformation (T) is another important SSM concept that is *weltanschauung* (W) or the worldview. Together, T and W are the core of CATWOE analysis. As a guide to establishing root definitions, Checkland (1981) provides the CATWOE elements by which a complete root definition should identify the Customers (C), the Actors (A), the Transformation process (T), the *weltanschauung* (worldview) (W), the Owners (O) and the Environment (E).

The CATWOE mnemonic is associated with the following definitions:

- **Customers:** the victims or beneficiaries of the transformation;
- **Actors:** those who will do the transformation;
- **Transformation process:** the conversion of input to output;
- ***Weltanschauung***: the worldview which makes this transformation meaningful in context;
- **Owner(s):** those who could stop the transformation;
- **Environmental constraints:** elements outside the system which it takes as given.

Essentially, CATWOE incorporates the identified transformation and subsequently forces five questions, the answers to which are deemed necessary if a transformation is to begin to be understood contextually (Georgiou, 2008). In Table 3.1 these questions are shown, along with some of the main information sources.

Table 3.1 – The elements of a CATWOE and their basic information sources (Georgiou, 2008).

Mnemonic	Terms	Questions	Source
C	Customers	Who will benefit and who will lose from this T?	Analysis 1 and 3
A	Actors	Who will do the T, or make it happen physically?	Analysis 1 and 3
T	Transformation process	The T itself	Methodological rules
W	"Weltanschauung"	What reason or perspective justifies doing T?	Analysis 2
O	Owner	Who can stop or change the T?	Analysis 1 and 3
E	Environmental constraints	What restrictions are there in the immediate surroundings of T?	Analysis 2

The conceptual model should incorporate processes of monitoring and control, which establish measures of performance. Monitoring and control processes are described in terms of efficacy, efficiency, and effectiveness ("3Es") according to Checkland & Scholes (1990). Efficacy normally refers to verify if the system works; efficiency is used to assess if the transformation is being achieved with minimum use of resources, and effectiveness is used to evaluate if the system is working according to the long-term aim.

After subscribing root definitions, the next stage focuses on modelling the activities within the system. The conceptual model happens in the “system thinking” world and is an analytical part of understanding the problematic situation. Modelling is based on the root definitions and the CATWOE elements; it is done by using verbs to describe activities and by assembling a handful of such activities structured in terms of logical dependence (Checkland, 1981). To build the conceptual model, it is recommended to use 7±2 activities, excluding monitoring and control activities, based on a work which suggests that the human brain may have the capacity to cope with around seven concepts simultaneously (Miller, 1956).

3.3.3 Debating and taking action in the situation

In the comparison stage, systems thinking provides a structure for a debate about changes aimed at improving the system performance as a result of the insights captured in root definitions (Checkland, 1981). Structure to the discussion is provided by using models as a source of questions about the situation (Checkland and Poulter, 2010).

Checkland (1981) described four ways of doing the comparison (informal discussion; formal questioning; scenario writing based on “operating” the models; and trying to model the real world in the same structure as the conceptual models) (Checkland, 1981). Of these, formal questioning has emerged as by far the most common (Checkland and Scholes, 1990).

The models are used as a source of questions to ask the real world and answering those questions initiates debate, which may be conducted in any way seeming appropriate to the particular situation. This stage allows to identify inadequacies in the initial analysis or in root definitions, which leads to the discussion of possible changes to be implemented for real world improvements based on the logic of the conceptual model. These changes could be in structure, in procedures and in attitudes.

3.4 Structuring decision objectives using Value Focused Thinking

The use of PSM such as SSM can be quite helpful to the process of identifying relevant actors and objectives (Neves *et al.*, 2009), but even when the DM has all the relevant information related to the process, that information frequently remains unstructured (Tsoukiàs, 2007). It is required greater depth, clear structure, and a sound conceptual base in developing objectives for strategic decision contexts (Keeney, 1996). Identifying and properly structuring decision objectives is essential to increase the effectiveness in decision making, but often the DM fails at this crucial stage (Bond, Carlson and Keeney, 2010).

Keeney (1992) proposed the Value Focused Thinking (VFT) approach, which aims to identify what is valued by a DM and why it is worthy of thought for any decision situation (Keeney, 1992). The general principle of thinking about values is to discover the reason for each objective and how it relates to other objectives. The core of VFT emphasizes that the DM should focus first on values and later on alternatives, which leads to increase the creativity in designing new alternatives, while assuring evaluation criteria meet personal's or organization's objectives. Objectives (or points of view of the DM) express the identified values in a more specific and coherent way directed to decision making (Keeney, 2008).

According to Keeney (1992), each fundamental objective should be controllable, essential, concise, specific and understandable. Fundamental objectives often encompass different sub-objectives. However, each fundamental objective should enable to assess independently the alternatives. The set of fundamental objectives should be complete and not redundant. In decisions where the functions of the alternatives are the same, or are not relevant, it may be useful to group the objectives by categories to help the structuring process.

Fundamental objectives concern the ends that DM value in a specific decision context; means-objectives are ways to achieve ends (Keeney, 1992). As an example, a means-objective regarding building energy performance improvement would be to minimize the energy costs, while the fundamental objective would be to maximize the energy savings.

Structuring a functional value hierarchy into a criteria tree can be carried out using two classical approaches: top-down or bottom-up (Keeney, 1992; Belton, Ackermann and Shepherd, 1997; Franco and Montibeller, 2010; Parnell *et al.*, 2013). The top-down approach identifies the fundamental objectives, which are then decomposed into lower-level sub-objectives, down to the relevant attributes of the alternatives. This process focuses on the main concerns underlying the evaluation process, although relevant sub-objectives risk to be omitted. A bottom-up approach starts by identifying which attributes distinguish the alternatives, and then these attributes are grouped by their nature and these groups could be further grouped into higher-level objectives. This process allows discussing objectives at a more tangible and comprehensive level, although a broader perspective risks being missed.

The strategy followed in this thesis sought to combine the use of SSM for unveiling and structuring the relevant evaluation aspects with VFT used for refining these aspects as objectives to be further converted into criteria to be included in an MCDA model.

3.5 Multi-criteria decision methods

In general terms, when the set of alternatives under evaluation is discrete, their evaluation can be divided into two stages. Initially, the performance of each alternative is evaluated in each criterion. Afterwards, the scores in each criterion are aggregated to obtain a global assessment, considering a multi-criteria structure of preferences and values.

Evaluating alternatives, even considering a single point of view, can be complex and encompassing multiple criteria. It is necessary to define how to measure the performance of each alternative in each criterion: it could be through a natural attribute of the alternative directly related with assessed objective (e.g., the net floor area of a building), a proxy attribute indirectly related with the assessed objective (e.g., the CO_2 concentration level inside a room to assess the indoor air quality), a constructed attribute or by defining a qualitative assessment scale (Keeney and Gregory, 2005) .

Depending on the nature of the criteria, the scales used to measure their performance can be ordinal or cardinal. Ordinal scales are used when there is a finite, and generally small, set of qualitative performance levels. In this situation, when numbers are assigned to the performance levels, they do not express any quantity, but only a rank. Using those numbers for performing arithmetic and statistics calculations is a common mistake (e.g., using median values). Cardinal scales use numbers to express quantitative performance levels, where the value differences can be compared (e.g., interval scales: temperature expressed in °F or °C). The ratio scales have all the properties of an interval scale and have a clear definition of an absolute zero (e.g., monetary scales), leading to compare the ratio of two measurements.

Usually, a performance matrix is made to summarise the performance of each alternative in each of the evaluation criteria. Except in the cases where a dominance relation is identified, the comparison of two or more alternatives requires that value trade-offs are identified, considering that some criteria may have more importance than others. At this stage, the multi-criteria preference's aggregation method should be selected and parameterized.

There are several categorizations of MCDA methods, with a fuzzy definition of the boundaries between categories. Generally, there are three types of preference aggregation methods (Roy, 1985; Schärlig, 1985):

- **unique synthesis criterion approach**, disregarding any incomparability, or complete aggregation methods;
- **outranking synthesis approach**, accepting incomparability, or partial aggregation methods;
- **interactive local judgement approach** with trial-error iterations or methods of local agreggation.

The unique synthesis criterion approach aims at determining a global performance score in which a given alternative is evaluated through the aggregation of the individual performances in each criterion. A typical method of this type is the weighted sum of the performances (Yoon and Hwang, 1995). One of the methods with more theoretical foundations for modelling the DM's preferences is the additive utility or value function (Keeney, 2006). Other approaches are the Ordered Weighted Average (OWA) (Yager, 1988) or the fuzzy integrals, such as Choquet and Sugeno integrals (Grabisch and

Labreuche, 2010). All these preference aggregation approaches evaluate each alternative independently from others. Nevertheless, it is assumed that there is compensation between criteria. It is also possible to include in the unique synthesis criterion methods some approaches that assign a score to each alternative based on pairwise comparisons between the alternatives' performances in each criterion. The most well-known approach of this type is the Analytic Hierarchy Process/Analytic Network Process (AHP/ANP), in which pairwise comparisons between criteria and between alternatives (using a ratio scale) are made by the DM (Saaty, 2008). The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) can also be included in this typology of methods, in which the global score of an alternative is determined considering its nearest distance to the ideal solution (the best in each criterion for the set of alternatives) and the farthest distance to the negative-ideal solution (the worst in each criterion for the set of alternatives) (Yoon and Hwang, 1995).

The outranking synthesis approach methods are used in two main phases: firstly, the outranking relations between the alternatives are constructed trough a procedure of criteria aggregation; then, the outranking relation is explored according to the decision problem typology to be appraised. The outranking relation is richer than the dominance relation, though poorer/weaker than a preference relation in complete aggregation methods (Belton and Stewart, 2002). Thus, the preference model allows for incomparability between alternatives whenever sufficient information to support another decision is not available.

The family of ELECTRE (*Elimination Et Choix Traduisant la REalité*) methods, developed by Bernard Roy and its co-workers, has been widely applied to a vast range of multi-criteria real-world decision problems, "ranging from agriculture to environment and water management, from finance to project selection, from personnel recruiting to transportation" (Roy and Bouyssou, 1993; Figueira, Mousseau and Roy, 2005; Figueira *et al.*, 2013). Preference Ranking Organization for Enrichment Evaluation (PROMETHEE) is another family of methods, also grounded in the concept of outranking relations. This family was created as a simplest alternative to the use of ELECTRE (Brans, Vincke and Mareschal, 1986). Generally, these methods rely on pairwise comparisons of each criterion performance between alternatives, such as a tournament. The ELECTRE TRI method, devoted to sorting problems, is an exception since the alternatives under evaluation are assigned to pre-defined ordered categories according to their absolute performance in comparison to reference profiles, and not in comparison with other alternatives performance.

The interactive local judgement approach with trial-error iterations or methods of local agreggation aims at exploring the efficient boundary, typically using interactive algorithms where the set of non-dominated solutions[2] is computed and then the DM are asked to decide which results are acceptable (concluding the process) or which characteristics of the current solution(s) they would like to seek to improve by providing additional information. Based on this information a new step of computation is made to present another set of solutions to DM and a new step of dialog (interaction) will occur until the solutions are accepted (Bouyssou *et al.*, 2006). Most of the mehtods in this group are devoted to the choice decision problem, representing extensions of multiobjective programming (Roy and Bouyssou, 1993).

Considering the objectives of the work presented in this thesis, the option to formulate the problem as a sorting approach is the most appropriate, since it aims at evaluating the alternatives in terms of their absolute merits (without comparing with the remaining alternatives). The assignment of the alternatives to the categories of merit is based on the pairwise comparison of each alternative with the reference actions that define the boundaries of the categories. The outcome of this process can be used to benchmark the alternatives and identify possible examples to follow, as well as defining priorities for the implementation of energy performance improvement measures. During the structuring stage (Chapter 4), ELECTRE TRI, which is summarized in the following section, turned out

[2] A solution is nondominated whenever there is no other feasible solution that simultaneously improves all the objective function values, i.e., improving an objective entails deteriorating, at least, one of the other objective function values. In general, while the designation of efficient solution is referred to points in the decision variable space, the designation of nondominated solution is used for points in the objective function space. When used in a generic way in this text, the designations of efficient and nondominated solution are used interchangeably.

as the method that best suits the desired characteristics of the multi-criteria approach to use in the appraisal stage.

3.5.1 ELECTRE TRI method

The ELECTRE-TRI method (Yu, 1992b) belongs to the ELECTRE family of multi-criteria methods developed by Roy and his co-workers (Roy, 1991; Roy and Bouyssou, 1993). This method is devoted to sorting problems, which aim to assign a set of alternatives a_i ($i=1,...,m$) into predefined ordered categories according to a set of n evaluation criteria g_j ($j=1,...,n$). Each category C^h ($h=1,...,k$) is bounded by two reference alternatives (actions, profiles), in terms of performance in each criterion: b^h is the upper limit and b^{h-1} is the lower limit (Figure 3.3).

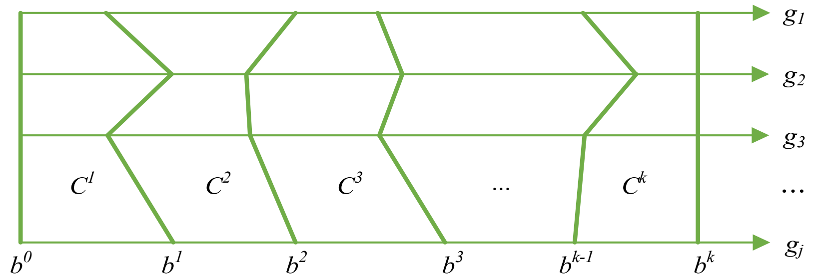

Figure 3.3 – Definition of categories in ELECTRE TRI using reference profiles - adapted from (Dias and Mousseau, 2003b).

The reference profiles related to each criterion g_j may be associated with indifference (q_j), preference (p_j) and veto (v_j) thresholds. The indifference and preference thresholds allow for some imprecision and gradation when evaluating alternatives against reference profiles: scores in criterion g_j are considered indistinguishable if their difference is q_j or less and one score is considered undoubtedly better than another one if their difference is p_j or more. The veto threshold (v_j) aims at introducing a non-compensatory element in the decision process, i.e., vetoing the conclusion that an alternative is at least as good as the reference profile if the former is much worse than the latter by a difference greater than v_j according to g_j.

The assignment of an alternative into a category is based on the comparison of its performances in each criterion to the reference profiles. This comparison aims at exploring an outranking relation between alternatives and the reference profiles (denoted $a_i \, S \, b^h$). An alternative a_i outranks the reference profile b^h if it is at least as good as the latter one (i.e., a_i is not worse than b^h) considering the performances of a_i and b^h in each criterion. If a_i is not worse than b^h in every criterion, then $a_i \, S \, b^h$. However, if there are some criteria for which a_i is worse than b^h then a_i may still outrank b^h or not, depending on the relative importance of those criteria and the differences in the scores in face of the threshold values (small differences may be ignored, whereas very large differences may oppose a veto to the outranking).

Considering a given alternative a_i and a profile b^h, the concordance (c_j) and discordance (d_j) indices (Figure 3.4) for each criterion, g_j, are computed according to the following expressions.

$$\Delta_j(a_i, b^h) = \begin{cases} g_j(a_i) - g_j(b^h), \ if \ g_j \ is \ to \ be \ maximized \\ g_j(b^h) - g_j(a_i), \ if \ g_j \ is \ to \ be \ minimized \end{cases} \quad (1)$$

$$c_j(a_i, b^h) = \begin{cases} 0, \ if \ \Delta_j < -p_j(b^h) \\ \frac{p_j + \Delta_j}{p_j - q_j}, \ if -p_j(b^h) \leq \Delta_j < -q_j(b^h) \\ 1, \ if \ \Delta_j \geq -q_j(b^h) \end{cases} \quad (2)$$

$$d_j(a_i, b^h) = \begin{cases} 1 \quad , \ if \ \Delta_j < -v_j(b^h) \\ \frac{-\Delta_j - p_j}{v_j - p_j}, \ if -v_j(b^h) \leq \Delta_j < -p_j(b^h) \\ 0 \quad , \ if \ \Delta_j \geq -p_j(b^h) \end{cases} \quad (3)$$

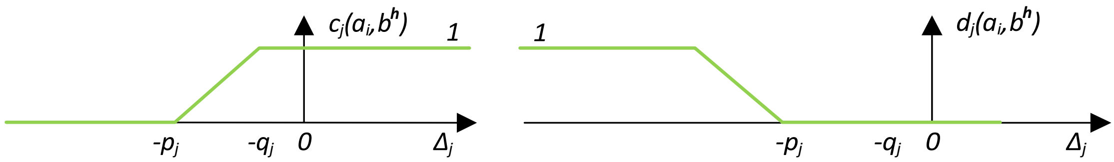

Figure 3.4 – Concordance (left) and discordance (right) indices for the criterion *j*.

The global multi-criteria concordance index accounts for the relative importance of the coalitions of criteria that agree that a_i outranks b^h ($a_i \, S \, b^h$). In the ELECTRE TRI method, the weight assigned for each criterion (k_j) is not intended to convert its performance into a common value scale, but it represents a true importance factor. Moreover, weights are scale independent. In this setting, weights should be interpreted as the “voting power” of each criterion to establish the outranking relation. Thus, the n single criterion concordance indices are aggregated into a global multi-criteria concordance index, considering the relative weight of each criterion k_j, as follows:

$$c(a_i, b^h) = \frac{\sum_{j=1}^{n} c_j(a_i, b^h) \cdot k_j}{\sum_{j=1}^{n} k_j} \quad (4)$$

The credibility degree index of the outranking relation, σ (a_i,b^h), is computed based on the formerly presented indexes, summarizing the arguments for and against the assertation that $a_i\ S\ b^h$. Despite there are several different expressions to compute the credibility degree index, in this thesis the following expression will be used (Dias and Mousseau, 2003b):

$$\sigma(a_i, b^h) = c(a_i, b^h).\,[1 - d^{max}(a_i, b^h)] \quad (5)$$

where: $d^{max}(a_i, b^h) = max_{j\in\{1,\ldots,n\}}\, d_j(a_i, b^h)$ (6)

The validation of the outranking relation is made by comparing the credibility degree index with a cutting level λ (with λ ∈ [0;1]), which indicates whether the credibility is significant or not, according to the rule: $a_i\ S\ b^h \Leftrightarrow \sigma(a_i,b^h) \geq \lambda$. If $\sigma(a_i,b^h) \geq \lambda$ and $\sigma(b^h,a_i) \geq \lambda$ then a_i is indifferent to b^h; if $\sigma(a_i,b^h) \geq \lambda$ and $\sigma(b^h,a_i) < \lambda$ then a_i is preferred to b^h ($a_i\ S\ b^h$ and not $b^h\ S\ a_i$); if $\sigma(a_i,b^h) < \lambda$ and $\sigma(b^h,a_i) \geq \lambda$ then b^h is preferred to a_i ($b^h\ S\ a_i$ and not $a_i\ S\ b^h$); if $\sigma(a_i,b^h) < \lambda$ and $\sigma(b^h,a_i) < \lambda$ then a_i and b^h are incomparable (not $a_i\ S\ b^h$ and not $b^h\ S\ a_i$).

In the ELECTRE TRI method there are two approaches (optimistic and pessimistic) to assign an alternative to a predefined category, differing in the way an alternative a_i compares with the reference profiles. Whenever the alternative to be sorted is incomparable[3] to some profiles, the pessimistic perspective places it in a lower category than the optimistic perspective; otherwise, both perspectives sort it in the same category. In the work developed in this thesis, the pessimistic perspective will be used, according to which each alternative a_i is assigned to the highest category C^h such that a_i outranks

[3] According to Dias and Mousseau (2018), incomparability typically occurs when the strengths and weaknesses of two alternatives are so different that one cannot conclude that one is better than the other, but it is equally unwarranted to conclude that they are indifferent (i.e., similarly preferred).

b^{h-1}, i.e., an alternative is sorted in a category C^k if it is good enough to outrank its lower bound but not good enough to outrank its upper bound (Dias and Mousseau, 2018).

To address specific requirements, new variants of ELECTRE TRI have been proposed, making this method suitable to deal with a large variety of sustainability assessment contexts. Thus, the use of ELECTRE TRI in sustainability assessments, among other applications, is expected to grow and to keep improving in the future (Dias, 2021).

The decision support software package *IRIS - **I**nteractive **R**obustness analysis and parameters' **I**nference for multi-criteria **S**orting problems* (version 2.0) was selected to deal with the model developed. This decision support system (DSS) has been designed to assist the assignment of actions described by their performances in multiple criteria to a set of predefined ordered categories, using a pessimistic concordance-only variant of the ELECTRE TRI method (Dias and Mousseau, 2003a, 2003b), accepting uncertainty in the input parameters and the inclusion of veto effects (Dias *et al.*, 2002).

The IRIS DSS allows for considering imprecision associated with the cutting level through the DM's definition of acceptable intervals for this parameter. The DM may also define linear constraints on the criterion weights, which may be indirectly expressed by the definition of assignment examples, where the user defines the worst and best categories for some of the alternatives, according to their holistic judgment. These assignment examples are translated into constraints on the parameter values, meaning that the initial assignments of ELECTRE TRI should restore these examples and classify the alternatives accordingly (Dias and Mousseau, 2003b).

3.6 MCDA in building energy and sustainability performance

This section presents the relevant findings from literature in the field of multi-criteria decision aid on buildings energy and sustainability assessment.

Nielsen et al. (2016) performed a literature review related to the development of decision support tools applicable in the pre-design and design phase of building renovation projects and found that there has been a continuous development of decision support tools applied to building renovation since the mid-1990s, varying in methodological approach, complexity, and sustainability objectives. Six areas where decision support tools can assist the renovation process were also identified: goal setting, weighting of criteria, building diagnosis, generation of design alternatives, estimation of performance, and finally evaluation of design alternatives (Nielsen *et al.*, 2016).

A literature review was also conducted in the scope of this thesis to identify the most significant MCDA methods, and their applications, related to building energy and sustainability performance assessments, complementing the previous findings. Table 3.1 summarizes the papers considered relevant, in the scope of the present thesis, to deal with the evaluation of energy and sustainability issues using MCDA methods. The year of publication of each reference is also included.

Table 3.1 – MCDA methods applied for building energy and sustainability assessments.

Reference	**Year**	**Method(s)**	**Application**
(Balcomb and Curtner, 2000)	2000	AHP	Selection of design options in the preliminary design process of buildings, based on the evaluation of building performance simulations results.
(Blondeau, Spérandio and Allard, 2002)	2002	MAUT and a combination of ELECTRE I, ELECTRE II and ELECTRE IV	Selection of a suitable ventilation strategy in a university building to ensure the best possible indoor air quality, thermal comfort, and the lower energy consumption.
(Roulet *et al.*, 2002)	2002	ELECTRE III and IV	Rating to qualify and to sort various retrofitting scenarios based on energy use and thermal comfort conditions.
(Rey, 2004)	2004	ELECTRE III	Ranking different retrofitting strategies in office buildings.
(Avgelis and Papadopoulos, 2009)	2009	ELECTRE III	Ranking a set of six different HVAC systems in a university building considering economic, energy, user's satisfaction, and environmental criteria.
(Al Waer and Clements-Croome, 2010)	2010	AHP	Identification and selection of Key Performance Indicators for sustainability assessment of intelligent buildings, inferring their relative importance.
(Mróz, 2010)	2010	ELECTRE III	Selection of the most appropriate integrated heating-cooling system for an office building.
(Medineckiene and Björk, 2011)	2011	SAW, COPRAS, MEW and AHP (weighting the criteria)	Selection of energy performance renovation measures, using SAW, COPRAS and MEW methods, according to four criteria: use of energy, investment cost and payback period; including owners' preferences. The AHP method was used to define the criterion weights.
(Lee and Lin, 2011)	2011	TOPSIS	Ranking the energy performance of 47 office buildings in Taiwan.
(Merad *et al.*, 2013)	2013	ELECTRE III and MAUT (Choquet integral)	ELECTRE III was used for ranking actions to implement sustainable development principles in a French Institute. Then, an MAUT based aggregation was used to prioritize the implementation of a set of 20 operational actions.
(Villarinho Rosa and Haddad, 2013)	2013	AHP (weighting the criteria)	Weighting the relative importance of criteria and sub-criteria in a system for sustainability assessment and evaluation of environmental aspects and socioeconomic perspectives of existing buildings in Rio de Janeiro, Brazil.
(Silva and Almeida, 2013)	2013	ELECTRE III	Selection of construction solutions for a refurbishment project considering their impact on the energy performance, thermal and acoustic comfort, indoor air quality and environmental impact of the building.

Table 3.1 – MCDA methods applied for building energy and sustainability assessments. (continued)

Reference	Year	Method(s)	Application
(Banfill, and Strachan, 2014)	2014	DELPHI	A two-stage Delphi to identify a set of criteria for the selection of energy performance improvement measures (first stage), and then to establish weightings for each criterion (second stage).
(Markl-Hummel and Geldermann, 2014)	2014	PROMETHEE	Ranking a set of energy retrofitting alternatives for a primary school in Germany towards climate change protection.
(Medineckiene *et al.*, 2015)	2015	AHP and ARA	Evaluation and selection of the best performing alternative in terms of the building sustainability based on Swedish certification system using the method ARA, where criteria weights were determined using the AHP method.
(Mulliner, Malys and Maliene, 2016)	2016	WSM, WPM, (revised) AHP, COPRAS and TOPSIS	Comparison of six different multi-criteria decision-making approaches (WSM, WPM, (revised) AHP, COPRAS and TOPSIS) for ranking the sustainable housing affordability in Liverpool.
(Si *et al.*, 2016)	2016	AHP	Comparative assessment and ranking of energy retrofitting measures using AHP in a university building in London, considering economic and environmental criteria.
(Seddiki *et al.*, 2016)	2016	DELPHI, SWING and PROMETHEE	Delphi was used to define the evaluation criteria and the thermal renovation solutions to evaluate; SWING was used to facilitate the definition of the criteria weights; and PROMETHEE methods were used to obtain a global ranking of the thermal renovation solutions of a building envelope in Algeria.
(Lizana *et al.*, 2016)	2016	SAW	Partial effectiveness indices are computed for each stakeholder profile (private users of dwellings, public promoters, and private promoters) and then aggregated as a global effectiveness index for evaluating different energy retrofit measures for residential buildings in terms of environmental, economic, and social aspects.
(Fernandes, 2017)	2017	DELPHI and MACBETH	Identification and selection of relevant criteria for evaluating the energy management performance in Higher Education Institutions. Delphi was used for assessing the criteria relevance and MACBETH was used to aggregate the different criteria into a global performance score.
(Tupenaite *et al.*, 2017)	2017	AHP	Identification and ranking of a hierarchically structured system of sustainability indicators for evaluating new housing projects in the Baltic States, based on three sustainability dimensions: environmental, social and economic.
(Wang *et al.*, 2017)	2017	TOPSIS	Benchmarking and rating the energy performance of a set of 324 residential dwellings in Iowa, United States, through seven numerical performance indicators derived from the yearly energy consumption data and related independent variables data.
(Fouchal *et al.*, 2017)	2017	TOPSIS	Generation of building retrofit alternatives and ranking them using energy performance analysis, user requirements, relevant benchmarks, and regulations. The alternatives are selected based on a large pool of alternatives combination and target values for the selected criteria predefined by users.
(Invidiata, Lavagna and Ghisi, 2018)	2018	AHP and COPRAS	Selection the best design strategies to improve sustainability of a case study multi-family social building located in Milan. COPRAS was used for ranking the design strategies, while criteria weights were determined using AHP.
(D'Agostino, Parker and Melià, 2019)	2019	MAUT	MAUT was used to assess and rank a set of energy efficiency measures with the aim of maximizing annual energy savings and minimizing embodied energy and investment costs.
(Dell'Anna *et al.*, 2020)	2020	PROMETHEE II	Ranking 16 alternative energy efficiency measures for NZEB according to energy consumption, life-cycle costs, carbon emissions, property value and indoor comfort. Methodology applied to a single-family residential building located in Piedmont, Italy.

Table 3.1 – MCDA methods applied for building energy and sustainability assessments. (continued)

Reference	Year	Method(s)	Application
(Napoli *et al.*, 2020)	2020	ELECTRE TRI	Sorting energy retrofitting actions into categories of overall performance, according to different aspects (energy efficiency, financial-economic feasibility, and environmental protection). This approach aims at supporting the public decision process of establishing priorities for funding the different retrofitting actions.
(Ongpeng *et al.*, 2020)	2020	AHP and VIKOR	Ranking three energy retrofit scenarios towards transforming existing buildings into NZEB, according to environment, economy, and technical criteria. AHP was used for criteria weighting and VIKOR for ranking the alternatives.
(Becchio *et al.*, 2021)	2021	TOPSIS and SWING	Ranking eight alternative energy efficiency scenarios for retrofitting the university campus of Politecnico di Torino. The evaluation criteria were weighted using SWING method and TOPSIS was used to rank the alternatives according to nine criteria considering economic, technical, environmental, and social aspects.
(Bertoncini *et al.*, 2022)	2022	PROMETHEE II	Ranking retrofit scenarios for neighbourhood regeneration using a set of energy, environmental, economic, and social criteria. The methodology was applied to a case study in Italy, and it was combined with the use of DesignBuilder and EnergyPlan software.
(Sarmas, Marinakis and Doukas, 2022)	2022	TOPSIS	A dataset of energy efficiency projects from Latvia was evaluated based on energy reduction per cost, energy reduction percentage per cost, building age and building consumption per heating floor area. TOPSIS was used to classify each project into one of five categories.

From the analysis of Table 3.1, it should be noted that AHP, TOPSIS and ELECTRE III are the most popular methods used to deal with building energy and sustainability decision problems. This can be partially attributed to the fact that the most frequent typology of decision problem found in the literature reviewed is the ranking problem. Moreover, AHP is frequently used not only as an MCDA method for criteria aggregation, but also as a method for defining the criterion weights to be used in other methods.

3.7 Concluding remarks

In this chapter, the background on MCDA that is relevant for the work reported in this thesis was presented. The review included methodologies used at the structuring stage, with emphasis on SSM and VFT, which were used in Chapter 4 for structuring the multi-criteria energy and sustainability performance assessment of school buildings. Afterwards, the multi-criteria ELECTRE TRI method was also summarized since it was considered to have the most adequate characteristics to be used in the evaluation stage. ELECTRE TRI is devoted to sorting problems: the alternatives under evaluation are assigned to pre-defined ordered categories of merit according to their absolute performance, i.e., independently of other alternatives' performance, thus enabling to assess alternatives on an as-they-come basis. Reference profiles defining the boundaries of the categories are used to sort each alternative. This method enables incorporating the DM's preferences by means of coefficient of importance assigned to each criterion (weights) as well as indifference, preference, and veto thresholds. Different (quantitative or qualitative) scales may be used for different criteria (Roy and Bouyssou, 1991; Yu, 1992b, 1992a; Maystre *et al.*, 1994).

Then, a concise literature review on the application of MCDA methods in the field of energy and/or sustainability assessment in buildings was presented. This review revealed that the most frequent use of MCDA approaches found was related to the evaluation of sets or individual design/retrofit actions for improving the energy and/or sustainability of buildings. It was found that there are few studies using MCDA methods for performing the evaluation of the energy and sustainability performance of buildings. Thus, the study presented in this thesis will contribute to address this gap, since it aims at classifying the energy and sustainability performance of school buildings into categories or classes of merit, while including also non-energy criteria.

Chapter 4 Structuring the multi-criteria evaluation problem[4]

This chapter presents a comprehensive problem structuring approach combining SSM and VFT to elicit and organize the multiple aspects that influence energy efficiency of school buildings. The main aim of this stage is structuring the fundamental objectives to develop a tree of objectives to be further converted into criteria to be included in the MCDA model to be used by management entities for rating the overall energy and sustainability performance of school buildings.

4.1 Introduction

A proper structuring phase of an MCDA approach is not only the first part of the process, but also the most useful part for the formulation of any decision aid model (Beinat and Bana e Costa, 2005).

The work presented in this chapter bridges the human-centred and technical-centred perspectives concerning the assessment of energy efficiency in school buildings. The decision context is inherently unstructured with multiple stakeholders with potentially conflicting perspectives and interests. According to our experience in energy planning problems, the use of PSM offers a valuable analytical framework for unveiling and structuring the relevant evaluation aspects. The VFT approach is then used to refine these aspects as objectives to be further converted into criteria to be included in an MCDA model, which is aimed at classifying the energy performance of school buildings taking also into consideration non-energy aspects. Similar approaches were followed in the context of

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[4] This chapter is based on the paper: Bernardo, H., Gaspar, A. and Henggeler Antunes, C. (2018) 'A Combined Value Focused Thinking-Soft Systems Methodology Approach to Structure Decision Support for Energy Performance Assessment of School Buildings', Sustainability, MDPI, 10(7).

sustainable urban energy planning (Coelho, Antunes and Martins, 2010), analysis of energy efficiency measures (Neves *et al.*, 2004), decision-making support to a sustainable building renovation process (Kamari, Corrao and Kirkegaard, 2017), identification of opportunities for managing energy and utility usage in textile manufacturing processes (Ngai *et al.*, 2012), energy behaviour modelling (Lopes, Antunes and Martins, 2015), renewable energy projects selection (Bortoluzzi *et al.*, 2021), and also within the EU-funded project STEEP—*Systems Thinking for Energy Efficient Planning* for developing energy master plans for districts in three European cities (Yearworth, 2015; Freeman and Yearworth, 2017).

4.2 Identification of stakeholders

In Chapter 3, the SSM was presented as a PSM method used for unveiling information from complex decision situations. Thus, drawing a rich picture is one of the most widely known device of SSM to represent visually the structures, processes, stakeholders, relationships, culture, conflicts, issues, etc. in the situation under analysis (Checkland, 2000).

The diagram presented in Figure 4.1 was built using information in the scientific literature on methods used for assessing energy performance of buildings, technical visits to Portuguese schools in different geographical locations, and discussions with experts from the University of Coimbra, the R&D institutes INESC Coimbra and ADAI, the school management company, facilities management companies, equipment manufacturers and retailers, members of the board of directors of schools, students, and members of the parents associations.

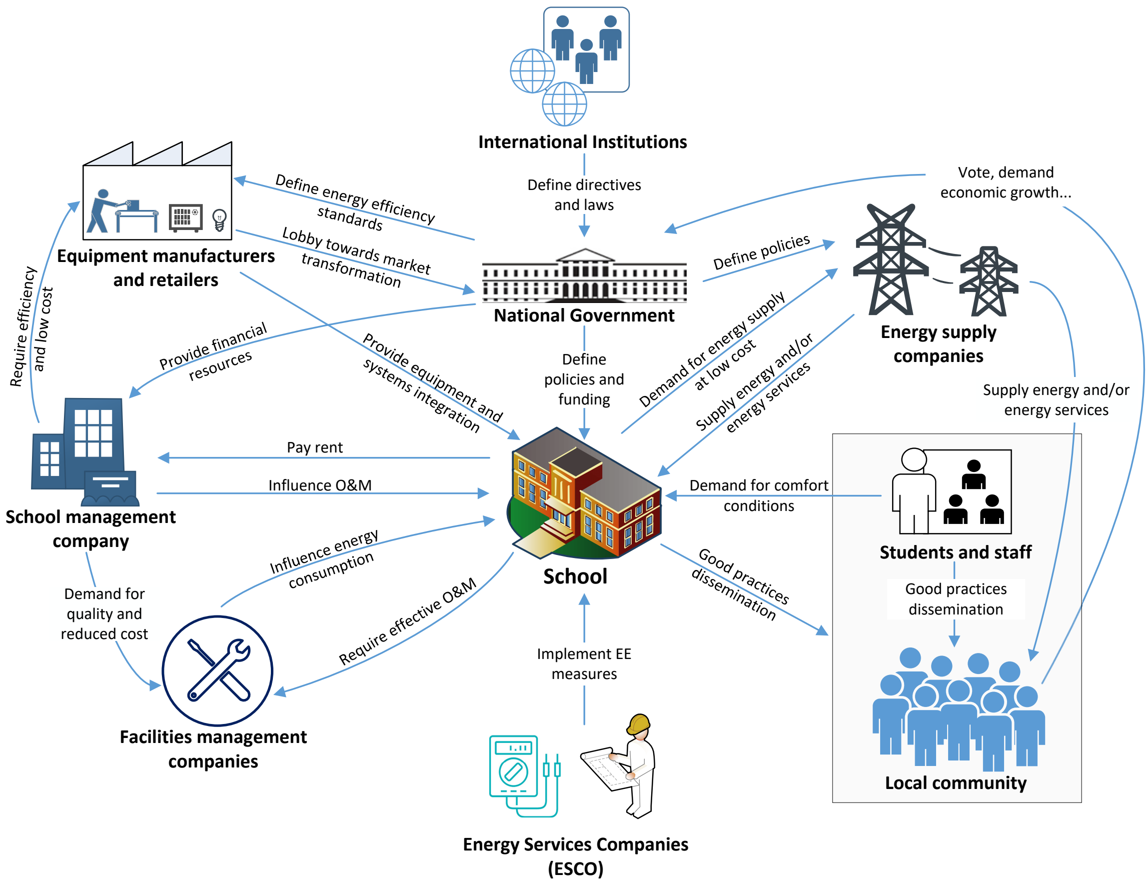

Figure 4.1 – Rich picture of stakeholders involved in school buildings energy management (Bernardo, Gaspar and Henggeler Antunes, 2018).

The rich picture was complemented with the inquiry process named Analyses One, Two and Three (Checkland, 1981; Checkland and Scholes, 1990; Checkland and Poulter, 2010), which focus on the intervention itself, a social analysis and a political analysis, respectively. This helped grasping the problematic situation as comprehensively as possible. The most relevant stakeholders identified and their roles in the process are described below.

International institutions influence the main directions to be followed in terms of energy policy, defining standards and directives to disseminate the application of energy efficiency improvement programs and actions (e.g., European Commission).

National government implements international directives towards the development of national regulatory and policy frameworks for energy and environment, setting targets and goals to be achieved in what concerns energy consumption and GHG emissions reductions and promoting the market transformation regarding the dissemination of energy efficiency initiatives. It is also responsible for providing funding for school operation and legislation to be accomplished in terms of energy performance and indoor air quality. The national government is also responsible for paying the school buildings management company the fee for managing a schools' modernisation programme.

School management company is responsible for planning, managing, developing, and implementing a modernisation programme for the public network of secondary and other schools under the responsibility of the national government (Ministry of Education). It is an independent state-owned company, but it functions as a private sector company, with administrative and financial autonomy and capability to take a commercial approach to managing the procurement and maintenance. It is funded by the fee that it is paid by the national government for managing the modernisation programme and the rent paid (through schools' budget) once the work has been completed. Nevertheless, it is subject to the supervision of the Portuguese government ministers responsible for the areas of finance and education. The relationship between this company and the government has been regulated by two instruments: a public service agreement that sets out both the obligations for implementing the modernisation programme and the fee for managing it; an infrastructure availability and operations agreement which sets out the rent to be paid to the company and the obligations for maintenance (Blyth *et al.*, 2012). This company along with schools' management boards may apply for the implementation of energy efficiency projects, through national and international programs as well as energy performance contracts with energy services companies.

Energy supply companies supply the energy demanded by consumers, with whom they have a commercial relation; electrical energy and natural gas retail companies, in liberalised markets, were the focus in this study. Energy efficiency can be a new business opportunity, a marketing tool, or a threat (due to loss of energy sales) for these companies. The main goals of these companies are to achieve low costs, high revenues, reliability of supply and compatibility with existing energy infrastructures. In the future, increasing interest in energy infrastructures improvement is expected, mainly in a scenario of a widespread development of smart grids and smart energy management devices.

Energy services companies provide energy services and implement energy efficiency measures, avoiding or reducing the operational costs and environmental impacts of school facilities at low risk to owners; their business model is grounded on energy performance contracting, which consists of the implementation of energy efficiency measures with a contractually agreed level of energy-related cost savings that covers the investment cost of the project. In the framework of ECO.AP Programme (ADENE, 2011), which aims at promoting the implementation of building renovations and plans to improve energy efficiency in the long term in public buildings through the establishment of energy performance contracts, these companies have an important role related to public buildings.

Equipment manufacturers and retailers sell equipment and systems that can enhance the energy performance of the buildings; they can be compelled to introduce into the market equipment with improved energy efficiency through standards or mandatory labelling schemes, or they can use energy efficiency as a marketing tool to promote their products. The equipment and systems provided can influence the degree of improvement of the building, e.g., the BACS installed in a school may turn impossible to implement some types of control strategies to reduce the energy consumption and improve energy management. In addition, these companies develop lobbying which can influence the legislation design using energy efficiency concerns as a marketing tool towards market transformation. They could be beneficiaries of the system as they can increase the sales due to legislative requirements, but they may also be victims because they are required to offer efficient equipment at low cost.

Facilities management companies provide services related to integrated technical management, planning, O&M, with the aim of supporting and improving the effectiveness of building's facilities and infrastructures. Effective FM encompasses multi-disciplinary activities within the built environment and the management of their impact upon people and the workplace. This activity has the responsibility of keeping a safe and efficient learning and working environment. Thus, the O&M of facility's equipment and systems may significantly influence the overall energy performance of each school. These companies are required to deliver quality of service at competitive costs.

School encompasses the school building and its facilities, including the management board. To provide a proper learning environment, schools are required to provide good indoor environmental conditions generally leading to increasing energy consumption and energy costs. To reduce operational costs while providing adequate indoor environmental conditions to the occupants, organizations should manage their buildings taking energy efficiency into consideration due to high energy costs. The management board has the responsibility of defining policies for energy management and setting targets and goals in terms of energy efficiency, according to budget restrictions and guidelines from the school buildings management company. The decisions made may influence the occupant's behaviour related to the efficient use of energy and resources and, consequently, the local community energy behaviours could also be influenced through the dissemination of good practices.

Students and staff are the occupants of the school building, which could be the beneficiaries or the victims of the indoor environmental comfort (or the lack of it) provided by the building's facilities. Their behaviour and productivity are influenced by the indoor environmental conditions, including adequate lighting and acoustic conditions, thermal comfort, and indoor air quality. They could act also as drivers for the dissemination of good practices in the local community.

Local community is formed by students' and staff's families and neighbours who can learn from and adopt the good practices implemented in the school by means of actions to reduce energy bills and afford more and better energy services (heating, cooling, etc.) at homes. It is important to have a positive impact on public opinion and local community because they have power to influence decisions of some stakeholders, e.g., the management board of schools could be influenced through the parents' associations and the local/national government could be penalized or beneficiated in elections for the policies undertaken. The local community can also benefit from the potential indirect effects of schools' energy efficiency investments and actions through job creation as well as enhanced health and well-being resulting from less pollution and the improvement of IEQ.

4.3 Root definition

As it was stated in Chapter 3, a root definition can be defined as a sentence describing the fundamental nature of a system when perceived from a distinct viewpoint as a transformation process.

The first approach for improving the situation is to develop a system to understand, manage and help to continuously improve energy efficiency and IEQ in Portuguese school buildings. The root definition could be described as: *A system to classify school buildings into categories of energy performance, considering multiple energy and non-energy related aspects, to provide decision support to the school management company for improvement of energy management through the definition of energy policies and energy related investments*.

As it was mentioned in Section 3.3, CATWOE incorporates the identified transformation and subsequently forces five questions (Georgiou, 2008). Table 4.1 presents these questions, along with the CATWOE mnemonic definitions for the situation under analysis.

Table 4.1 – The elements of a CATWOE and their root definition.

Mnemonic	Terms	Questions	Answers/definitions
C	Customers	Who will benefit and who will lose from this T?	School, students and staff, local community, and national economy
A	Actors	Who will do the T, or make it happen physically?	International institutions, national government, school buildings management company, energy supply companies, energy service companies, equipment manufacturers and retailers, facilities management companies, school, students and staff, local community.
T	Transformation process	The T itself (conversion of input to output)	Understanding the energy performance of schools, leading to the improvement of energy management and definition of energy policies and energy related investments, through an appropriate performance classification of each school building.
W	"Weltanschauung"	What reason or perspective justifies doing T?	There are several energy and non-energy related decisions affecting or being affected by the energy performance of school buildings that should take into consideration the stakeholders' preferences.
O	Owner	Who can stop or change the T?	School management company, on behalf of the national government
E	Environmental constraints	What restrictions are there in the immediate surroundings of T?	Capability to collect all relevant data; ability to challenge current planning and operation; funding and technological constraints; legislation and directives.

4.4 Conceptual model

After completing the root definition, the next stage focuses on modelling the activities within the system. The conceptual model developed for the classification of school buildings into categories of performance is shown in Figure 4.2.

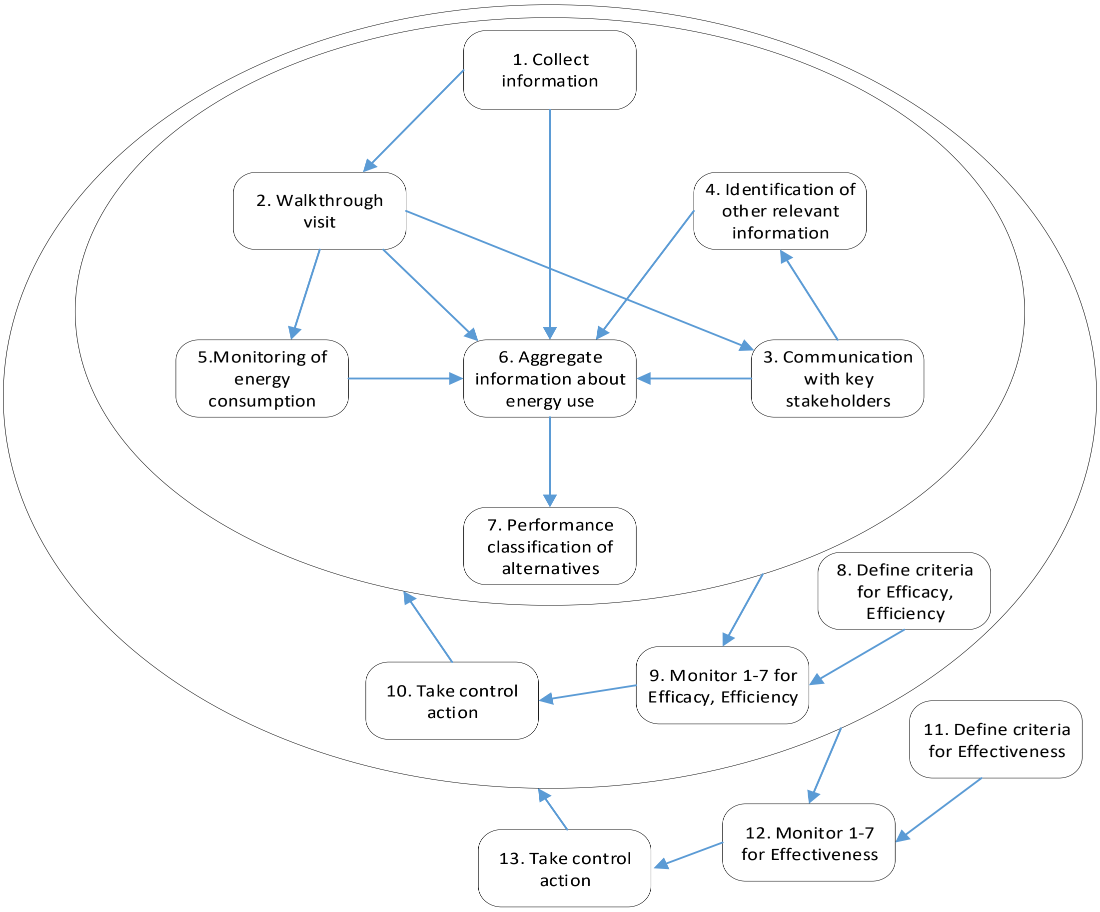

Figure 4.2 – Conceptual model of the classification system.

Activity 1 analysed energy bills and typical occupancy data, as well as other relevant variables (number of meals served, etc.). The analysis also included architectural and engineering plans of each building and its energy related systems (HVAC, pumps, lighting, domestic hot water, etc.). This information enabled to identify the main topics to be clarified during the on-site visit.

Activity 2 involved the inspection of building facilities to examine actual systems and get answer to questions from the preliminary review. Comments from the staff were considered and further readily available data were collected to get a more comprehensive view of the building technical facilities. To identify additional measurement needs, measurement instrumentation and the type of recorded data were verified.

Activity 3 was performed during and after the site visit, where some meetings with the main stakeholders were made to establish a common understanding of the building facilities, its management principles and comfort conditions provided. During the meetings, individual questionnaires, and informal inquiry questions to collect data were performed. This activity was useful to help in Activity 4, regarding identifying and collecting other relevant information for the classification process.

Activity 5 was useful because it allowed the quantification of energy flows, the knowledge of energy load profile and the assessment of the facility's energy performance. The measured energy data were complemented with IEQ related data, enabling the incorporation of comfort issues in the evaluation model.

Activity 6 consisted of the aggregation of all relevant energy and non-energy information for the energy performance classification system. At this stage, the stakeholder's objectives and values are converted into criteria taking into consideration all quantitative and qualitative information relevant for the evaluation.

The classification of school buildings according to their performance is made in Activity 7, which is the aim of the proposed system. This process emphasizes the need for a multi-criteria method incorporating the objectives and values of the DM and other stakeholders into the decision support process (Keeney, 1992).

The definitions of the principles to evaluate the system, according to the root definition, in terms of "3Es" are:

- **Efficacy:** The system identifies correctly all relevant parameters to rate the energy performance of a school building, including relevant non-energy aspects.
- **Efficiency:** The system works with the minimum resources necessary.
- **Effectiveness:** A school building well classified by the MCDA tool will be used as reference for implementing its energy efficiency solutions in other schools.

The "3Es" are continuously monitored and reported. A similar analysis was undertaken from the perspectives of the school management company, on behalf of the national government. This company has an important role in providing guidance and oversight, and it focuses on the outcome of the process. In the context of energy efficiency of school buildings, the analysis of the evolution of performance enables monitoring the efficiency ("will it work with minimum resources?"—expressed in costs, energy, and water) and controlling the system's efficacy ("is the school assuring the appropriate indoor environmental conditions to the occupants?"). Concerning effectiveness, good performing schools will be used as reference for the improvement of other schools. To achieve effectiveness, an energy management scheme focused on continuous improvement strategies should be implemented so that the savings remain over time.

4.5 Comparison and debate

In the present work, the comparison was made in an informal way although supported with a formal questioning. The model built was used for comparison and debate about the proposed approach versus the real world. From the comparison and debate, some important issues emerged about assessing the energy efficiency of schools considering the management company's perspective.

The system was compared to the Portuguese Buildings' Energy Certification Scheme[5] (MEE, 2013), mainly in what concerns non-residential buildings. In such a scheme, buildings energy performance is assigned to a predefined label (eight values from A+ to F), according to a ratio between the actual energy usage indicator and a reference energy usage indicator, in terms of primary energy. Despite not having impact on the energy label assignment, school buildings should comply with indoor air quality requirements. Our study focused on performing a demand-side analysis of the buildings' energy consumption. Therefore, instead of primary energy, final energy consumption will be used as a criterion in the MCDA model, enabling a direct comparison with other buildings in terms of the amount of energy supplied to the facilities.

Another important issue discussed and considered relevant relates to the incorporation of non-energy aspects in the evaluation system. In 2014, the IEA published the report "Capturing the Multiple Benefits of Energy Efficiency", where the need to identify, quantify and assess the multiple benefits of energy efficiency is addressed and encouraged. In the report, the notion that energy efficiency helps to achieve a much broader range of outcomes contributing to improve welfare and wealth is highlighted (OECD/IEA, 2014).

[5] Despite the update to national legislation regarding building energy performance certification (SCE) in 2020 (PCM, 2020), energy performance label categories (A+ to F) have not been rescaled.

Moreover, the project "COMBI—Calculating and Operationalizing the Multiple Benefits of Energy Efficiency in Europe" has been funded by the European Union's Horizon 2020 research and innovation programme (Ürge-Vorsatz *et al.*, 2016). The aim of the project is identifying and estimating the energy and non-energy impacts that a realisation of the EU energy efficiency potential would have in the year 2030, which demonstrates the relevance of the approach followed in our study.

School buildings are spaces where it is required that adequate indoor environmental conditions should be provided to the occupants, so that they can achieve the educational goals. Therefore, multiple non-energy aspects should be considered when addressing energy efficiency assessment. Nevertheless, an important concern that emerged from the discussions was the effect of using the savings of bill reduction due to energy efficiency actions to increase the use of other energy services to improve comfort and health conditions of the students, e.g., adequate ventilation of classrooms. These actions could even result in (slightly) increasing energy bills, the so-called rebound effect (Barker, Ekins and Foxon, 2007; Sorrell and Dimitropoulos, 2008). In schools, the rebound effect can be seen as an opportunity to increase the indoor environmental conditions without increasing the energy bill, rather than a negative impact of energy efficiency actions.

The fact that, due to budget restrictions, in some of the schools visited during this work the board of directors decided to parameterize the BACS to keep the HVAC systems active only during a limited time of the occupancy period, leading to measured indoor CO_2 concentrations too high in certain periods, should be considered when analysing the typical pattern of a working day. Too high peak values undermine the indoor air quality in the remaining occupancy time of the classroom, harming the work conditions for teachers and students. We performed a simulation study of one of the schools analysed, where it is shown that it is possible to extend the use of mechanical ventilation according to the required enhancement of indoor air quality. This action combined with the adoption of new lower fresh air flow rates would improve air quality while avoiding excessive cost and without requiring any investment (Bernardo, Quintal and Oliveira, 2017).

The discussion and debate stage was fundamental to the identification of the stakeholders' values and objectives that are presented and structured in the following section.

4.6 Structuring the fundamental objectives

The use of the SSM approach, together with literature reviews on energy performance assessment methodologies, was useful to reveal a "cloud" of objectives reflecting attributes that should be evaluated when assessing the energy efficiency of school buildings. The objectives identified do not have a defined structure or hierarchy. The concepts and methods presented in Keeney (1992) were used to elicit and structure objectives (or points of view of the DM) obtained from the SSM application.

To structure objectives into hierarchies, two important structures were defined, the hierarchy of fundamental objectives and the network of means-ends objectives.

The interrelated values about the same fundamental concerns were grouped into categories, which are associated with fundamental aspects for assessing the energy performance of schools. The categories can be seen as the top of a functional value hierarchy, which is a combination of the functional hierarchies from systems engineering and the value hierarchy of decision analysis (Parnell *et al.*, 2013). In this work, the methodology proposed by Parnell *et al.* (2013) was followed, where the hierarchy should begin with a statement of the primary objective. Then, at the top level of the structure, the functions (categories) formed by the fundamental objectives (rather than means-objectives) appear. The fundamental objectives can be decomposed into lower-level objectives.

The resulting list of fundamental objectives associated with the purpose of using energy efficiency as a "resource" to reduce costs and improve indoor environmental conditions in schools is described below, with no particular sequence concerning priorities or preferences.

Objective 1: to decrease the school's energy consumption. The main concern related to energy efficiency in buildings is how to achieve a reduction of the final energy consumption with repercussion on operation costs and the environment (due to related GHG emissions). These reductions could also be achieved using renewable energy sources, which should be used in addition to the implementation of demand-side energy efficiency measures. Any energy efficiency measure taken will have direct impact on the building energy consumption. The energy supply companies can also benefit from the demand-side energy efficiency improvement lowering costs for energy generation, transmission and distribution, improving system reliability and the possibility of delaying or deferring capital investments on systems and grid upgrade. This objective can be decomposed into two lower-level objectives, according to the energy sources used:

- *Electrical energy consumption:* It accounts for electrical energy that is delivered to the building by the utility. This could be expressed through the amount of electrical energy supplied to the building per unit of floor area during a period of a year. This measurement could incorporate the effect of renewables, since if there is on-site renewable electricity production, the amount of electricity supplied by the grid will decrease.
- *Natural gas consumption:* It accounts for natural gas that is bought from the utility. This could be expressed through the amount of natural gas delivered to the building per unit of floor area during a period of one year. Similar to electrical energy, this measurement could incorporate the effect of renewables, e.g., if there are solar thermal collectors for hot water heating, the natural gas required from the grid for that purpose should be reduced.

Objective 2: to benefit the global environment. Climate change mitigation is nowadays one of the most important challenges. Usually, in what regards energy consumption, the main climate change mitigation strategy is reducing the fossil fuels dependence and its gradual replacement by renewable energy sources. Reducing energy demand through energy efficiency actions has achieved a significant role in the mitigation of GHG emissions with some benefits in terms of cost-effectiveness and reaching the reduction targets. The waste of water is also an important environmental issue, since it contributes to water scarcity, ecosystems degradation and to increase its price. Improving the energy efficiency and maintenance of the systems and equipment used for water treatment, heating, pumping, etc. can contribute to reduce the water needed for each usage. Reducing the wastewater leads to environmental benefits but can also contribute to decrease the energy consumption (and related GHG emissions) and cost of wastewater treatment. Since there was also mention of other impacts, this objective was defined by means of three lower-level objectives:

- *Greenhouse gases emissions:* It encompasses the emissions of GHG that impact global warming related to energy purchased by the school. It depends on the carbon intensity of the country's generation mix since it is calculated based on an emission factor of carbon dioxide defined for electricity and for natural gas. This impact is expressed in carbon dioxide (CO_2) equivalent units per unit of floor area during a period of one year.
- *Water consumption:* It accounts for the water consumption in the school for use in toilets, showers, food preparation, irrigation, etc., which represents a significant value of the operation costs of the building. It could be expressed through the amount of water delivered to the buildings per unit of floor area during a period of one year.
- *Visual impact:* It reflects the concern associated with building retrofitting and construction of new buildings that can affect the perception—positive or negative—that citizens have about the buildings, and potential long-term effects related to well-being in cities. The very subjective nature of this criterion suggests it should be measured on a qualitative basis.

Objective 3: to decrease the school's operation and maintenance costs. The O&M of school buildings includes costs for routine and preventive maintenance, minor repairs, cleaning, grounds keeping, energy, water, and security. Energy efficiency should be taken into consideration by schools to reduce operational costs and ensuring that equipment and systems are performing effectively and efficiently. This objective can be decomposed into three lower-level objectives, according to the typology of costs considered:

- *Energy cost:* It accounts for the cost of the school energy consumption. It is expressed through the amount of money paid to utilities per unit of floor area during a period of one year.
- *Water cost:* It accounts for the costs of the water consumption of the school. These costs also include municipal taxes due to discharge to the local sewer system and municipal solid waste treatment. This is expressed through the amount of money paid to the utilities per unit of floor area during a period of one year.
- *Maintenance cost:* It accounts for the costs that the school pays to the school management company for assuring the maintenance of the facilities. This is expressed through the amount of money paid per unit of floor area during a period of one year.

Objective 4: to benefit the indoor environmental quality of the schools. To provide adequate indoor environmental conditions, including thermal comfort, indoor air quality, lighting, and a quiet atmosphere, school buildings must spend a substantial amount of the annual budget in energy. Improving the energy efficiency of the systems devoted to ensuring adequate indoor environmental conditions have the potential to significantly reduce the incidence of allergies and respiratory diseases amongst vulnerable groups, such as children and teenagers. Likewise, health and well-being benefits, student's educational productivity may also increase with the improvement of indoor environmental conditions. This objective encompasses three lower-level objectives:

- *Indoor air quality:* It accounts for the air quality inside the rooms and the ventilation efficiency. Since the indoor air quality depends on the concentrations of gases and particles difficult to measure, the indoor CO_2 concentration is used as the performance indicator. The compliance percentage of CO_2 concentration with Portuguese legislation reference level is used as a measure of indoor air quality. The reference level is an average of the measurements over the whole occupancy period (MAOTESSESS, 2013).
- *Thermal comfort:* It accounts for the satisfaction degree of the occupants of a space with thermal environment. A widely used index for the assessment of thermal comfort is the predicted mean vote (PMV) (Fanger, 1972), which is measured in a bipolar scale [–3,3].
- *Other indoor aspects:* It accounts for other concerns related to indoor environmental conditions, such as visual comfort associated to the quality of the lighting and acoustic comfort related to the buildings' acoustic performance. The performance in this criterion was evaluated qualitatively.

Objective 5: to benefit the local community. One of the purposes of the modernisation programme was opening the schools to the communities, creating the conditions for closer cooperation links within the neighbourhood. The integration of energy efficiency related projects and activities in the annual educational project of the school appears to be an adequate way of raising awareness to energy efficiency issues and engage the whole school occupants and the local community in developing actions to foster the rational use of energy. In addition to the formal education of students, schools also play an important role in educating future generations of more energy aware consumers. Since there was also mention of other benefits, this objective was split into two lower-level objectives:

- *Energy awareness:* It accounts for the degree of energy awareness of the local community triggered by energy efficiency initiatives of the schools, e.g., through the promotion of “energy open days” or symposia to present results of students' projects to the community or by dissemination of information through the social media. The difficulty of measuring this criterion and its variable nature suggests a qualitative assessment.
- *Contribution for local development:* It accounts for indirect effects of schools’ energy efficiency investments and actions at a local level. Energy aware consumers can also take actions to reduce energy bills and have the ability to afford for more and better energy services (heating, cooling, etc.). The potential impacts are job creation, health and well-being benefits resulting from less pollution and the improvement of indoor environmental conditions (already accounted previously). This is dealt with as a qualitative criterion.

Objective 6: to improve school’s maintenance. Proper maintenance contributes to avoid or delay costly equipment upgrade investments, keep the health and safety of students and staff, and support educational performance. The BACS have gained a prominent role in the management of daily maintenance and energy-related operations with significant impact on the energy performance and IEQ of buildings. The technical maintenance staff engagement and training focused on energy efficiency, together with a lifetime commissioning approach to BACS, can lead to a significant reduction in utility costs. This objective can be split into two lower-level objectives:

- *Maintenance accomplishment:* It considers the implementation of preventive maintenance routines, standards and legal requirements compliance, existence of up-to-date reports and technical documentation, etc., that leads to an effective maintenance of the facilities. It is assessed as a percentage of compliance with a checklist provided by the facilities management company.

- *BACS performance:* It accounts for the knowledge and perception of the technical operators about the performance of BACS. The nature of this criterion suggests it should be assessed on a qualitative basis.

The final aim of the work presented in this chapter was to structure the objectives that emerged into a hierarchy. Figure 4.3 shows the resulting tree of objectives.

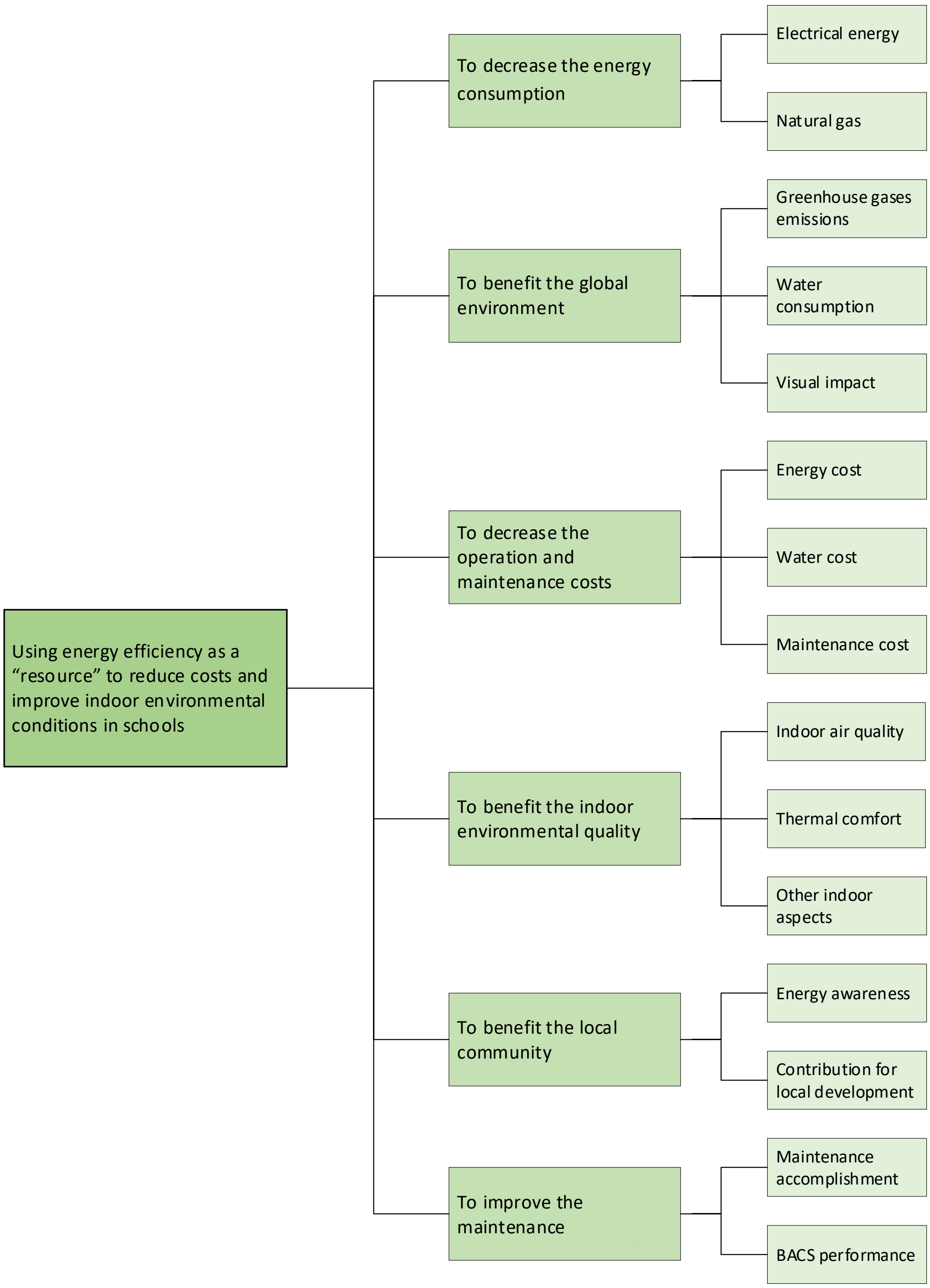

Figure 4.3 – Structured tree of fundamental objectives (Bernardo, Gaspar and Henggeler Antunes, 2018).

4.7 Concluding remarks

In this chapter, SSM combined with VFT was used for unveiling and structuring a set of fundamental objectives for evaluating the performance of school buildings considering multiple, conflicting, and incommensurate aspects influencing energy efficiency in schools.

The analysis of scientific literature, technical visits to schools in different regions, and discussions with key experts and stakeholders constituted the basis for the use of SSM for most relevant aspects that should be considered during the evaluation process. Then, the use of VFT combined the advantages of top-down and bottom-up approaches for structuring the fundamental objectives for a multi-criteria evaluation of school buildings' energy and sustainability performance. Initially, a bottom-up approach was performed to identify the set of fundamental objectives. Then, a top-down approach aimed at breaking down each objective into sub-objectives clarifying the essential issues at stake for performance measurement in each objective.

Analysing the general list of objectives presented previously, it seems that some impacts could be double counted (e.g., energy consumption contributes for O&M costs and for GHG emissions). Nevertheless, we carefully considered these issues for improving the clearness of the process, avoiding neglecting some concerns and different perspectives of the different stakeholders involved. For example, concerning energy consumption and GHG emissions, if two buildings have the same energy consumption, but one of them consumes a cleaner fuel, this building should not have the same level of penalization as the other building due to the energy consumption.

It should be noted that, at this stage, the technical visits revealed to be a key opportunity to explore and gain insights into the real-world operation conditions of school buildings across the country.

This work was essential for the evaluation stage in which the objectives identified were converted into criteria to score the alternatives' performance using the MCDA ELECTRE TRI method, incorporating the DM's preferences.

Chapter 5 Application of the MCDA model

This chapter describes the application of the MCDA model. It starts with a summary of the Portuguese school building stock and the context in which the *Secondary School Building Modernisation Programme* was launched by the Portuguese government. Then, the selection of the alternatives (schools) for evaluation in the framework of the 3Es Project is described, the criteria used in the MCDA model are specified, and the definition of the model's parameters is presented. The chapter ends with the presentation and analysis of results obtained from an interactive application of the MCDA model to evaluate school buildings.

5.1 Introduction

Public organizations, including governments and municipalities, from different countries have developed different types of school buildings for all levels of education, since the modern education system had emerged in western societies in the mid-19th century. Thus, the design and the construction of these buildings was guided by several principles and strategies towards the development of pedagogical and educational requirements (Alegre and Heitor, 2013). There is comprehensive literature available with detailed studies on architecture evolution of Portuguese school buildings (Alexandra Alegre *et al.*, 2010; Heitor and Marques Pinto, 2012; Alegre and Heitor, 2013).

The Portuguese school building stock is very heterogenous, in terms of building types, architectural features and facilities' quality. The schools built after 1970 are the prevalent type, following the extension of mandatory education and reflecting the expansion period in the school infrastructure. Concerning the school's layout, they evolve from a centralized building type with a compact configuration and an enclosed courtyard, to linear U, H, L or E shaped buildings, based on central corridor building type. At the end of the 1960s, aiming at reducing design and construction costs, standard design projects were adopted and this strategy was continuously used until the end of the 1990s.These buildings can be grouped in three different phases, accordingly to their built period: (1) from late 19th century up to 1935; (2) from 1935 to 1968; (3) from 1968 onwards (Heitor and Marques Pinto, 2012). The number of schools built in each period of construction since the late 19th century is presented in Table 5.1.

Table 5.1 – Summary of schools built in each period - adapted from (Alegre and Heitor, 2013).

Construction period	Typology of school building	Number of school buildings	Percentage [%]
1890s/1920s	Lycées	6	1.2
1930s	Modern schools	6	1.2
1940s/1950s	Plan 38	14	2.8
1950s/1960s	Plan 58 including: 1964 – 2nd standard design project (2 buildings) 1966 – 4th standard design project (2 buildings)	20	4.0
1960	1st standard design project*	70	14.1
1964	3rd standard design project*	2	0.4
1968	Normalised study for secondary schools	12	2.4
1970s/1990s	3x3 standard design, industrialised construction systems, prefabricated systems, etc. (pavilion type)	365	73.7
	Total	**495**	**100.0**

*Conceived for vocational schools

During the expansion period of school infrastructure, during the 1980s and early 1990s, the maintenance practices of the existing school building stock were neglected. Thus, the building stock show physical degradation and construction anomalies resulting in poor comfort conditions. Moreover, they were not adapted to the current needs in terms of educational strategies and practices (Heitor and Marques Pinto, 2012).

In this context, a major renovation programme named *Secondary School Building Modernisation Programme* has been launched by the Portuguese government in 2007. This initiative aimed at tackling the physical deterioration of the building stock in terms of energy performance and indoor environmental requirements, addressing comfort, sanitary standards and the functional adequacy of the buildings for teaching and learning, often with extension of the existing built area (Blyth *et al.*, 2012).

A state-owned company, Parque Escolar E.P.E., was created for planning, management, development, and implementation of this programme. Back in 2007, the Portuguese infrastructure of public secondary schools included 477 schools, predominantly built since 1968 (PE, 2009a). With the endeavour of raising the standards of educational facilities, Parque Escolar E.P.E. had envisaged the intervention in 332 schools by 2015 (i.e., 70% of the total secondary schools building stock in the country). By the end of 2009, the program involved 205 schools, and 4 consecutive phases: the pilot phase (Phase 0) involved only 4 schools; Phase 1 started in June 2007 and covered 26 additional schools; Phase 2 was initiated in March 2008 encompassing further 75 schools, and interventions had started in June 2009; finally, Phase 3 was initiated in April 2009 and it was supposed to cover 100 other schools (PE, 2009b). Early in the second half of 2011, in the context of an economic and financial crisis, the Portuguese government decided to implement a cost reduction plan, leading to the suspension of interventions in 34 schools in Phase 3 and all of Phase 4. The *Modernisation Programme* was recently resumed to conclude the unfinished works suspended since 2011[6].

This policy was launched under circumstances of strong public investment as part of a stimulus strategy aimed at boosting economic growth throughout the country. This context dramatically changed, and the economic crisis and severe financial constraints may be invoked to reinforce the value of carefully analysing the impact of this program, namely, to reduce the operating costs of refurbished schools. Therefore, an assessment of the programme focused on energy consumption and IEQ evaluation was performed in the framework of the 3Es Project. This R&D project was a partnership between University of Coimbra's R&D Units (ADAI, GEMF and INESC Coimbra) and TDGI (a facilities management company).

[6] *In* Marujo, Miguel. 2017. "Seis anos de aulas no meio do estaleiro". Diário de Notícias, 12 de setembro de 2017. https://www.dn.pt/portugal/seis-anos-de-aulas-no-meio-do-estaleiro-8763579.html, accessed 20 July 2022.

5.2 Selection of actions/alternatives for evaluation

Based on the analysis of a database (provided by the school management company) of 305 schools that were, or were expected to be, subject to refurbishment interventions under the *Secondary School Building Modernisation Programme*, a final selection of 8 school buildings was done for a thorough study, including energy consumption and operation conditions analysis. The criteria used for this selection were (sequentially applied):

- Balanced distribution by different geographic locations and climatic zones.
- Higher value of electrical energy use per gross floor area after the refurbishment.
- Higher ratio between the increase in electrical energy use per gross floor area and the increase of gross floor area after the refurbishment.
- Avaliability of the building pre-energy performance certification.

Since the R&D project aimed at evaluating the operation phase of the refurbished school buildings, the selection of the eight schools was restricted to buildings where the retrofit intervention was already finished and records of pre- and post-intervention energy demand were available. It should also be noted that, at this stage, the above-mentioned criteria were applied only to electrical energy consumption data, since the database did not provide information about other fuels used to feed the building energy needs.

Figure 5.1 shows the geographical location of climatic zones and the municipalities in the Portuguese mainland where the eight selected schools are located. The climatic zones are defined as “W” for winter (heating) season and “S” for summer (cooling) season; the numbers ranging from 1 to 3 indicate the climatic severity level, with the higher number representing the higher severity. The Climatic Map of Portugal, combining the different (winter and summer) climatic zones, was elaborated accordingly to *Regulamento das Características de Comportamento Térmico de Edifícios* (MOPTC, 2006)[7].

[7] The national legislation for building energy performance certification (SCE) was updated in 2013 (MEE, 2013) and in 2020 (PCM, 2020). Therefore, the presented school selection may have changed since some of the climatic zones have also changed (DGEG, 2013).

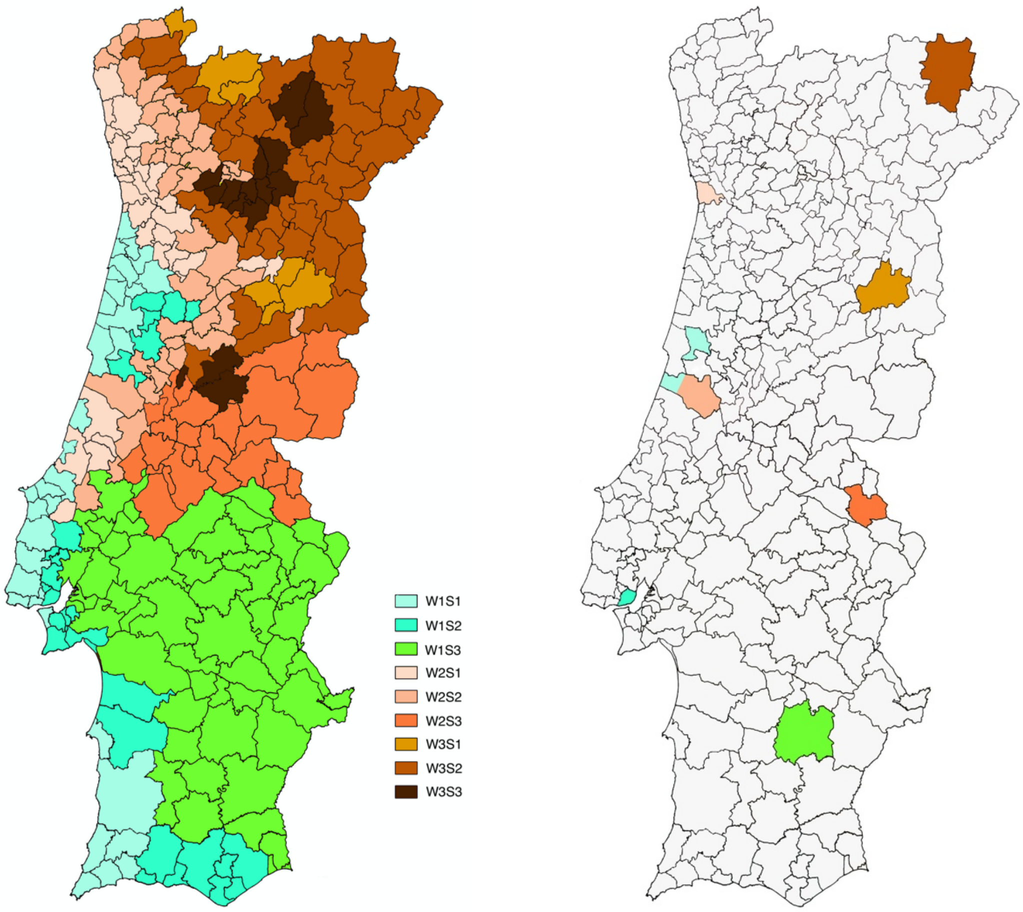

Figure 5.1 – Map of Portuguese mainland. a) Combination of climatic zones for the heating and cooling seasons. b) Selected schools (municipality).

A climatic zone data summary of each school under evaluation is presented in Table 5.2.

Table 5.2 – Municipalities of the eight schools selected, climatic zones, and heating degree-days.

Municipality	Climatic zone Selection phase / updated SCE	Heating degree days (HDD) Selection phase / updated SCE
Beja (BJA)	W1 S3 / W1 S3	1290 / 1145
Bragança (BGC)	W3 S2 / W3 S2	2850 / 2036
Guarda (GRD)	W3 S1 / W3 S2	2500 / 2235
Lisboa (LSB)	W1 S2/ W1 S2	1190 / 1022
Matosinhos (MTS)	W2 S1/ W1 S2	1580 / 1140
Montemor-o-Velho (MMV)	W1 S1 / W1 S2	1410 / 1265
Pombal (PBL)	W2 S2 / W2 S2	1580 / 1226
Portalegre (PTG)	W2 S3 / W1 S3	1740 / 1496

General information about each school under evaluation, along with a summary of the HVAC systems installed is presented in Table 5.3.

Table 5.3 – Brief presentation of the schools (alternatives) under evaluation.

School	General Information	HVAC system
	Year of construction: 1960 Year of retrofitting: 2008-2009 Gross floor area: 9435 m^2 Typology: Industrial and commercial technical school Location: Beja	Heating and cooling: centralised electrical air-water heat-pump. Domestic hot water: natural gas fired condensing boiler, supported by solar thermal panels. Mechanical ventilation: air handling units (AHU) with heating and cooling coils.
	Year of construction: 1962 Year of retrofitting: 2009-2011 Gross floor area: 11 619 m^2 Typology: Industrial and commercial technical school Location: Bragança	Heating and domestic hot water: natural gas fired boilers, supported by solar thermal panels. Cooling: centralised electrical air-water chillers. Mechanical ventilation: AHU with heating and cooling coils.
	Year of construction: 1969 Year of retrofitting: 2009-2011 Gross floor area: 14 894 m^2 Typology: Lyceum - Special design Location: Guarda	Heating and cooling: centralised electrical air-water heat-pumps (classrooms); Rooftop unit with an air-air heat pump and direct expansion variable refrigerant volume (VRV) systems (amphitheatre, canteen, library, and informatics classrooms). Domestic hot water: natural gas fired condensing boiler, supported by solar thermal panels. Mechanical ventilation: AHU with heating and cooling coils.
	Year of construction: 1969 Year of retrofitting: 2008-2010 Gross floor area: 9811 m^2 Typology: Lyceum pavilion type Location: Lisboa	Heating and domestic hot water: centralised natural gas fired boilers, supported by solar thermal panels. Cooling: centralised electrical air-water chiller. Mechanical ventilation: AHU with heating and cooling coils.
	Year of construction: 1969 Year of retrofitting: 2008-2010 Gross floor area: 12 693 m^2 Typology: Industrial and commercial technical school Location: Matosinhos	Heating and domestic hot water: centralised natural gas fired boilers, supported by solar thermal panels. Cooling: centralised electrical air-water chiller. Mechanical ventilation: AHU with heating and cooling coils.
	Year of construction: 1977 Year of retrofitting: 2009-2010 Gross floor area: 8326 m^2 Typology: 3x3 pavilion type Location: Montemor-o-Velho	Heating and cooling: electrical modular direct expansion VRV systems for each building. Domestic hot water: natural gas fired boilers (canteen/cafeteria and gymnasium), supported by solar thermal panels (only at gymnasium). Mechanical ventilation: AHU.
	Year of construction: 1963-1964 Year of retrofitting: 2009-2010 Gross floor area: 12 693 m^2 Typology: Industrial and commercial technical school Location: Pombal	Heating and cooling: electrical modular direct expansion VRV systems (administrative areas); centralised electrical air-water heat-pumps (classrooms); rooftop units with an air-air heat pump (meals hall, library, and auditorium). Domestic hot water: natural gas fired condensing boilers, supported by solar thermal panels. Mechanical ventilation: AHU with heating and cooling coils.
	Year of construction: 1976-1977 Year of retrofitting: 2008-2010 Gross floor area: 8866 m^2 Typology: Lyceum pavilion type Location: Portalegre	Heating and cooling: independent electrical air-water heat-pumps for each building (classrooms); rooftop unit with an air-air heat pump (library). Cooling: electrical air-water chiller (gymnasium). Domestic hot water: natural gas fired boiler, supported by solar thermal panels. Mechanical ventilation: AHU with heating and cooling coils.

5.3 Specification of criteria

For the parameterization of the MCDA model, the objectives identified in Chapter 4 were converted into criteria to evaluate the alternatives' performance using the ELECTRE TRI method. For instance, in Chapter 4, the objective *1. to decrease the school's energy consumption* was decomposed into two lower-level objectives (*electrical energy consumption* and *natural gas consumption*), but here it will be considered as a single criterion since each school has its own specificities in terms of end-use equipment, meaning that a particular energy service (e.g., heating, cooking) may be provided by electricity or natural gas in different schools.

Table 5.4 presents the summary of the key characteristics and the description of each criterion.

Table 5.4 – Criteria characterization and description.

Criterion		Evaluation scale/unit	Nature	Preference	Description
Energy consumption	g_1	[kWh/m^2]	Quantitative	Minimize	Yearly sum of electrical energy and natural gas supplied per unit of floor area. The energy amounts were gathered from the monthly utility invoices and used in terms of final energy.
Greenhouse gases emissions	g_2	[kgCO_2e/m^2]	Quantitative	Minimize	Yearly GHG emissions[8] resulting from the energy consumption per unit of floor area.
Water consumption	g_3	[m^3/m^2]	Quantitative	Minimize	Yearly sum of water supplied per unit of floor area. The amounts of water were gathered from the monthly utility invoices.
Visual impact	g_4	[1-5]	Qualitative	Maximize	Average value of the results of a questionnaire-based survey using a 5-point Likert ordinal scale applied to relevant stakeholders.
Energy cost	g_5	[EUR/m^2]	Quantitative	Minimize	Yearly sum of money spent in electrical energy and natural gas per unit of floor area.
Water cost	g_6	[EUR/m^2]	Quantitative	Minimize	Yearly sum of money spent in water (including wastewater and municipal solid waste treatment) per unit of floor area.
Maintenance cost	g_7	[EUR/m^2]	Quantitative	Minimize	Yearly sum of money spent in maintenance services per unit of floor area. The value obtained was the cost paid to the school management company.[9]

[8] The conversion factors used, accordingly to national legislation for building energy performance certification (SCE), were 0.144 kgCO_2e/kWh of primary energy (electrical energy) and 0.202 kgCO_2e/kWh of primary energy (natural gas) (DGEG, 2013).

[9] The value used for this criterion was based on "*Anexo IV, alínea A) Remuneração, componente de Serviços de Manutenção e Conservação – Triénio 2016/2018, do Contrato Programa Celebrado entre o Estado Português e a Parque Escolar, E.P.E.*".

Table 5.4 – Criteria characterization and description. (continued)

Criterion		Evaluation scale/unit	Nature	Preference	Description
Indoor air quality	g_8	[%]	Quantitative	Maximize	Percentage of compliance of indoor CO_2 concentration with the threshold mean value of 1250 ppm[10] over the occupancy period.
Thermal comfort	g_9	---	Quantitative	Minimize	The absolute peak value of PMV[11] was used to evaluate the satisfaction degree of the occupants of a space with the indoor thermal environment.
Other indoor aspects	g_{10}	[1-5]	Qualitative	Maximize	Average value of the results of a questionnaire-based survey using a 5-point Likert ordinal scale applied to relevant stakeholders.
Maintenance accomplishment	g_{11}	[%]	Quantitative	Maximize	Percentage of compliance with the implementation of preventive maintenance routines; standards and legal requirements; and the existence of up-to-date maintenance reports.[12]
BACS performance	g_{12}	[1-5]	Qualitative	Maximize	Average value of the results of a questionnaire-based survey using a 5-point Likert ordinal scale applied to BACS' operator of each school.
Energy awareness	g_{13}	[1-5]	Qualitative	Maximize	Average value of the results of a questionnaire-based survey using a 5-point Likert ordinal scale applied to relevant stakeholders.
Contribution for local development	g_{14}	[1-5]	Qualitative	Maximize	Average value of the results of a questionnaire-based survey using a 5-point Likert ordinal scale applied to relevant stakeholders.

The ELECTRE TRI method allows to deal effectively with criteria performances measured in different scales, including qualitative ones. In our approach 14 criteria were used: 9 expressed in quantitative scales and 5 expressed in a qualitative scale.

Most of the quantitative criteria presented above were used, whenever it was possible, using its natural scales. Concerning qualitative criteria, a 5-point Likert ordinal scale was used to evaluate the performance of each criterion, where each qualitative label was assigned to a number from 1 to 5 (Table 5.5).

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[10] The reference threshold of 1250 ppm was defined as an average of the indoor CO_2 concentration measurements in each space over the full occupancy period (MAOTESSESS, 2013). This criterion was computed as the average of the percentage of compliance in the two classrooms analysed in each school (Dias Pereira, 2016).

[11] Despite the PMV is expressed through a bipolar scale [-3; 3] (Fanger, 1972), in the present work, due to MCDA model implementation constraints, the absolute peak value of PMV was used, although negative and positive values may be considered differently to model thermal comfort, i.e., assigning different consequences to cold or hot conditions. This criterion was computed as the average of the simulated values of the two analysed classrooms in each school (Dias Pereira, 2016).

[12] The facilities management company computed this criterion as an overall maintenance accomplishment indicator, aggregating each key performance evaluation parameter with the following weights: implementation of preventive maintenance routines (50%), standards and legal requirements (25%), and the existence of up-to-date facilities maintenance reports (25%) (TDGI, 2015).

Table 5.5 – Quantitative criteria evaluation scale.

Criterion/scale	1	2	3	4	5
Visual impact	Strongly negative	Negative	Neutral	Positive	Strongly positive
Other indoor aspects	Very poor	Poor	Fair	Good	Very good
BACS performance	Very poor	Poor	Fair	Good	Very good
Energy awareness	Very poor	Poor	Fair	Good	Very good
Contribution for local development	Very poor	Poor	Fair	Good	Very good

When parameterizing the model, it was required to include several stakeholders' points-of-view, namely related to the buildings' qualitative assessment and to support the inferring of the model's technical parameters, such as reference profiles, thresholds, constraints on the criterion weights, existence of veto, and cutting levels (λ) for the credibility degree index of the outranking relation. Since this was a very interactive and participatory procedure, the insights of several stakeholders with different roles in the school building energy management process were included in formal and informal discussions to fine tune the MCDA model. Similar approaches were followed in the context of scenario planning. Table 5.6 presents an overview and examples of stakeholders contributing to the MCDA model parameterization based on the types of stakeholders identified in Andersen et al. (2021).

Table 5.6 – Types of model contributing stakeholders – adapted from (Andersen, Hansen and Selin, 2021).

Type of stakeholder	Contribution	Examples
Experts	Knowledge, experience, and expertise in the topic	Engineers, facilities managers, BACS operators, university professors and researchers
Stakeholder representatives	Viewpoints from representatives of organizations or groups with a stake in the outcome of the scenario process	Representatives of school management company, equipment manufacturers and retailers, facilities management companies and members of schools' management board
Personal stakeholders	Viewpoints from people with a stake in the outcome of the scenario process	High school teachers, school support staff and students
Citizens	Representative viewpoints of the general public with or without a direct stake in the outcome of the scenario process	Members of local community, teachers from other schools

In the following sections, the performance of each action in each criterion is presented, along with the reference profiles and threshold definitions. Moreover, the definition of the constraints on the criterion weights is also presented before the analysis of the results obtained.

5.4 Performance matrix, reference profiles and thresholds

The scores for each criterion were obtained from a field study and measurements carried out in a sample of 8 Portuguese secondary schools (the alternatives under evaluation). These values were computed according to the descriptions presented in Section 5.3 (Table 5.7).

Table 5.7 – Performance values for evaluation criteria.

Criterion/ alternative	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}	g_{12}	g_{13}	g_{14}
BGC	49.08	14.57	0.24	3.70	5.16	1.06	1.10	48.70	0.46	4.00	49.00	2.00	2.30	2.00
BJA	50.60	16.98	0.36	4.00	5.46	1.70	1.10	45.00	0.85	3.30	72.00	4.00	2.70	2.30
GRD	46.44	16.37	0.29	4.30	5.70	0.96	1.10	30.00	0.73	3.30	50.00	3.00	2.30	2.30
LSB	72.36	22.04	0.69	3.50	7.08	1.91	1.10	66.70	0.35	3.00	58.00	4.00	2.50	3.00
MMV	42.93	13.95	0.39	4.30	5.12	0.42	1.10	53.30	1.17	3.00	48.00	3.00	2.30	2.00
MTS	66.15	19.57	0.26	4.00	5.91	0.86	1.10	80.00	0.37	4.00	65.00	4.00	4.00	2.50
PBL	32.05	10.64	0.60	3.30	3.68	1.06	1.10	72.30	0.07	3.70	75.00	5.00	2.70	2.30
PTG	64.25	22.15	0.37	3.50	6.93	1.18	1.10	43.80	0.19	4.00	69.00	3.00	2.50	2.50

The aim of the classification system proposed is to rate buildings with the same typology, providing support to the DM (school management company) in broadcasting good practices, allowing "positive competition" between buildings and supporting decision making when defining priorities in investments in energy conservation. The number of categories has to be chosen wisely, kept to a minimum for simplicity and precision while addressing the need to differentiate different levels of performance. Thus, an eight-level system (A+ to F), such as the Portuguese Buildings' Energy Certification Scheme, was deemed excessive and a four-level system was used, comprising categories "Low" (C^1), "Average" (C^2), "Good" (C^3) and "Very Good" (C^4).

Afterwards, the categories were defined by specifying the upper and lower reference profiles, as well as the indifference (q_j), preference (p_j), and veto (v_j) thresholds for each criterion and reference profile. This process was supported by a panel of experts in building energy performance evaluation.

The definition of the indifference and preference thresholds was one of the most demanding tasks to perform with the support of experts due to the significant cognitive effort required to understand the requirements of a method unfamiliar to most of them.

An initial attempt to include their judgement, considering their personal knowledge and experience, resulted in an inconsistent output, with nearly all alternatives placed in the same category. Therefore, indifference and preference thresholds were set to 1% and 10% of the score ranges in each reference category (upper bound–lower bound), following the approach in Neves (2004).

Table 5.8 presents the reference profiles bounding each category for each criterion (also indicating whether the criterion is to be maximized or minimized), as well as the preference and indifference thresholds.

Table 5.8 – Reference profiles and thresholds.

Criterion/ parameter	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}	g_{12}	g_{13}	g_{14}
$g(b^1)$	65	20	0.52	2	6.5	1.5	1.65	55	0.65	2	25	2	2	2
q_1	0.15	0.03	0.0017	0.01	0.01	0.005	0.0055	0.15	0.0015	0.01	0.25	0.01	0.01	0.01
p_1	1.5	0.3	0.017	0.1	0.1	0.05	0.055	1.5	0.015	0.1	2.5	0.1	0.1	0.1
v_1	---	---	---	---	---	---	---	5	0.05	---	---	---	---	---
$g(b^2)$	50	17	0.35	3	5.5	1	1.1	70	0.5	3	50	3	3	3
q_2	0.05	0.03	0.001	0.01	0.015	0.005	0.003	0.15	0.003	0.01	0.30	0.01	0.01	0.01
p_2	0.5	0.3	0.01	0.1	0.15	0.05	0.03	1.5	0.03	0.1	3	0.1	0.1	0.1
v_2	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$g(b^3)$	45	14	0.25	4	4	0.5	0.8	85	0.2	4	80	4	4	4
q_3	0.45	0.14	0.0025	0.04	0.04	0.005	0.008	0.85	0.002	0.04	0.8	0.04	0.04	0.04
p_3	4.5	1.4	0.025	0.4	0.4	0.05	0.08	8.5	0.02	0.4	8.0	0.4	0.4	0.4
v_3	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Min/Max*	**-1**	**-1**	**-1**	**1**	**-1**	**-1**	**-1**	**1**	**-1**	**1**	**1**	**1**	**1**	**1**

* value 1 when the corresponding criterion is to maximize; value -1 when the corresponding criterion is to minimize.

To determine the criteria that should be subject to veto thresholds, a set of 17 stakeholders, mostly university professors and researchers with expertise on energy efficiency in buildings, was asked to answer the following question:

> *"Consider that a given school performs very well in all criteria except one. In your opinion, is there any criterion for which if its score is much worse than the reference value, this may oppose a veto to the advantages on the remaining criteria? If yes, please select a maximum of two criteria in these conditions".*

Table 5.9 presents the responses of each stakeholder about which criteria may be subject to a veto threshold.

Table 5.9 – Selection of veto thresholds for criteria: stakeholders' responses.

Criterion/ respondent	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}	g_{12}	g_{13}	g_{14}
1	---	---	---	---	---	---	---	1	1	---	---	---	---	---
2	---	---	---	---	---	---	---	1	---	---	---	---	---	---
3	---	---	---	---	---	---	---	1	---	---	---	1	---	---
4	1	---	---	---	---	---	---	1	---	---	---	---	---	---
5	1	1	---	---	---	---	---	---	---	---	---	---	---	---
6	---	---	---	---	---	---	---	1	1	---	---	---	---	---
7	---	---	---	---	---	1	---	---	---	---	---	---	---	---
8	---	---	---	---	---	---	---	1	1	---	---	---	---	---
9	1	---	1	---	---	---	---	---	---	---	---	---	---	---
10	1	---	---	---	---	---	---	---	1	---	---	---	---	---
11	---	---	---	---	---	---	---	1	1	---	---	---	---	---
12	---	---	---	---	---	---	---	---	---	---	1	1	---	---
13	---	---	---	---	---	---	---	1	1	---	---	---	---	---
14	---	---	---	---	---	---	---	---	---	---	---	---	---	---
15	1	---	---	---	---	---	---	---	1	---	---	---	---	---
16	---	---	---	---	---	---	---	1	1	---	---	---	---	---
17	---	---	---	---	1	---	---	---	1	---	---	---	---	---
Sum	**5**	**1**	**1**	**0**	**1**	**1**	**0**	**9**	**9**	**0**	**1**	**2**	**0**	**0**

Considering the responses of the stakeholders, the veto thresholds have been used only in the indoor air quality criterion (g_8) and the thermal comfort criterion (g_9), due to the importance of these criteria concerning the well-being of school building' occupants.

In what regards to indoor air quality criterion (g_8), none of the schools analysed comply with the average reference value (1250 ppm of indoor CO_2 concentration) over the full occupancy periods. Therefore, the veto threshold adopted was 50% of accomplishment with the reference value, bellow which none of the schools could be classified into a category better than C^1.

The definition of the veto threshold for thermal comfort criterion (g_9) was inspired by the categories defined in EN 15521 (CEN, 2007) for PMV, which recommends that values in the interval -0.5<PMV<+0.5 are considered "*Normal level of expectation and should be used for new buildings and renovations*" and values of PMV <-0.7 or PMV>+0.7 are considered "*Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year*". Thus, the value of 0.7 was considered the threshold for imposing a veto concerning thermal comfort criterion, above which none of the schools could be classified into a category better than C^1.

5.5 Definition of constraints on the criterion weights

In MCDA methods, the weights aim to represent, using different principles and aims, the relative importance assigned by a given DM to the criteria. In the ELECTRE TRI method, instead of converting the performance in each criterion into a common value scale, the weight assigned to each criterion (*kj*) represents its "voting power" to assess the validity of the outranking relation and it is scale independent. The imprecision of the DM's preferences associated with the criterion weights may be captured by linear constraints on the weights.

To incorporate the DM's preferences regarding weights, a convenience sample of 17 stakeholders, mostly university professors and researchers with expertise on energy efficiency interventions, was asked to rate the relative importance of each criterion according to a 5-point Likert ordinal scale. The responses of each stakeholder on each criterion are presented in Table 5.10.

Table 5.10 – Rating the relative importance of each criterion: stakeholders' responses.

Weight/ respondent	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9	k_{10}	k_{11}	k_{12}	k_{13}	k_{14}
1	4	3	4	3	4	4	4	5	5	4	4	3	3	3
2	4	4	4	2	4	4	3	3	3	3	2	2	3	2
3	4	3	4	3	4	4	4	5	5	4	4	4	5	3
4	4	4	4	2	3	2	3	4	3	3	1	1	1	1
5	5	5	4	3	5	5	5	5	4	4	3	3	3	3
6	5	4	5	3	4	4	4	3	4	4	4	2	5	3
7	4	4	4	4	4	4	4	5	5	5	4	4	5	4
8	5	4	3	1	5	3	4	4	5	3	3	4	3	3
9	5	5	5	5	2	4	4	4	4	4	4	3	5	2
10	5	4	4	3	5	4	5	5	5	5	3	4	4	4
11	5	4	5	4	4	4	4	5	5	4	5	5	4	4
12	3	3	3	3	4	4	4	4	4	3	5	5	3	2
13	5	5	5	3	4	4	4	4	4	3	4	4	4	3
14	4	5	5	3	3	3	3	4	4	4	3	3	4	3
15	5	4	3	4	5	3	4	4	5	4	4	3	3	2
16	4	3	5	4	5	5	5	4	5	4	5	4	4	3
17	4	3	4	4	5	5	5	4	4	4	5	5	3	4

All possible pairwise combinations between the criteria were compared to determine a set of linear constraints incorporating the stakeholders' points-of-view into the MCDA model. To determine the most representative linear constraints on the weight values, only the constraints where at least 16 out of 17 respondents considered one criterion more or equally important than the other were selected (Table 5.11).

Table 5.11 – Selection of constraints on the criterion weights.

N.	Constraint	N.	Constraint
1	$k_1 \geq k_2$	14	$k_7 \geq k_6$
2	$k_1 \geq k_4$ (*)	15	$k_7 \geq k_{14}$ (*)
3	$k_1 \geq k_{10}$	16	$k_8 \geq k_4$
4	$k_1 \geq k_{14}$ (*)	17	$k_8 \geq k_{10}$
5	$k_2 \geq k_{14}$	18	$k_8 \geq k_{14}$ (*)
6	$k_3 \geq k_4$	19	$k_9 \geq k_4$
7	$k_3 \geq k_{14}$ (*)	20	$k_9 \geq k_{10}$ (*)
8	$k_5 \geq k_4$	21	$k_9 \geq k_{14}$ (*)
9	$k_5 \geq k_6$	22	$k_{10} \geq k_4$
10	$k_5 \geq k_7$	23	$k_{10} \geq k_{14}$ (*)
11	$k_5 \geq k_{14}$ (*)	24	$k_{13} \geq k_{14}$
12	$k_6 \geq k_{14}$ (*)	25	$k_{11} \geq k_{14}$
13	$k_7 \geq k_4$	26	$k_{12} \geq k_{14}$

The constraints where 17 out of 17 respondents considered one criterion more or equally important than the other are also highlighted in the above-mentioned table using (*).

In addition to the linear constraints on the criterion weights inferred through the stakeholders' interaction, and since the focus of the study is the energy performance evaluation, we decided in dialogue with the experts to introduce additional constraints to ensure that the energy consumption criterion weight (k_1) is always higher than the weight of each of the remaining criteria.

In the following section, the results of the model applied to the selected set of school buildings are analysed to derive insights enabling to support the DM.

5.6 Analysis of results

The application of the MCDA model started with a small amount of information, as suggested by Dias *et al.* (2002). In this section, results obtained with different model parametrization sets are presented. The evaluation process started with the introduction in the IRIS software of the performance data for the eight schools according to the different criteria, the reference profiles, and the associated thresholds.

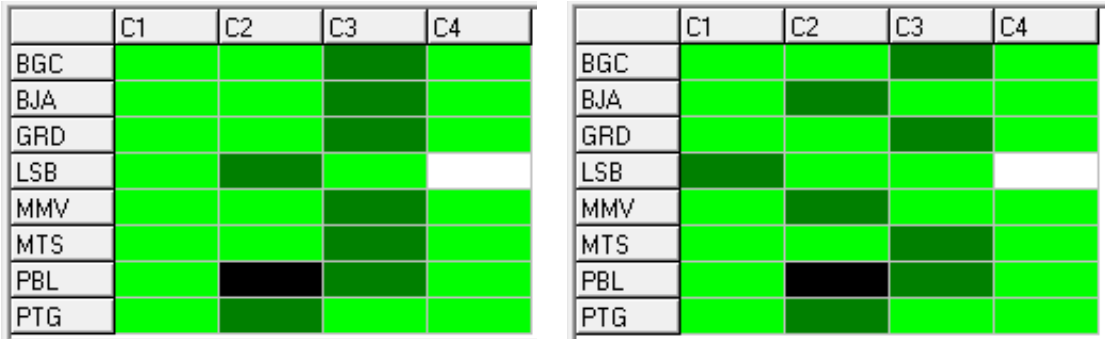
Initially, the cutting level (λ) was defined as simple majority $\lambda \in [0.51,1]$. This means that an alternative is at least as good as a category reference profile, only if at least 51% of the criterion weights "vote" for the concordance of the outranking relation. To improve the robustness and consistency of the results, the cutting level (λ) was then defined as a qualified (two-thirds) majority $\lambda \in [0.67, 1]$. This means that an alternative is at least as good as a category reference profile, only if at least 67% of the criterion weights "vote" for the concordance.

In the approach followed in this thesis, the weight bounds were defined within the interval $0.1 \leq k_j \leq 0.49$, j=1,...,14, thus ensuring that all criteria are considered in the evaluation and the maximum weight of each criterion is lower than the sum of the remaining criterion weights. Finally, further constraints on the range of the parameters were added (such as veto thresholds and classification examples); the DM may edit at any time the constraints that the weights and the cutting level should respect.

Firstly, the model was used with 12 criteria, and afterwards, 2 additional criteria were added to incorporate the evaluation of societal aspects (the energy awareness of the community and the contribution for local development) related with schools.

5.6.1 Model with 12 criteria

Initially, the model was applied using the criteria g_1 to g_{12}, without including any DM' constraint related to criterion weight preferences, and with the cutting level constrained to the intervals $\lambda \in [0.51;1]$ and $\lambda \in [0.67;1]$, corresponding to a simple majority requirement and a qualified majority requirement, respectively. The results obtained in these initial experiments are shown in Figure 5.2.



a) λ ∈ [0.51;1] b) λ ∈ [0.67;1]

Figure 5.2 – Initial results (12 criteria model).

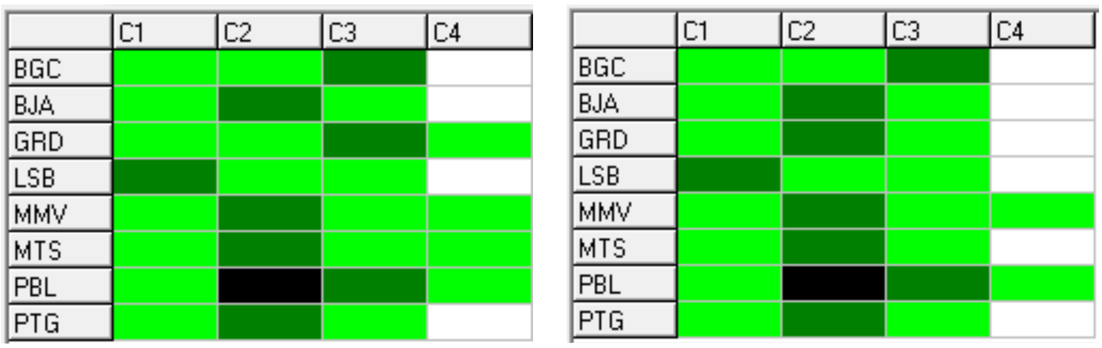
Figure 5.2, a) and b), shows the range of categories each alternative could be assigned to without violating any constraint for each of the predefined cutting levels. The darker green cells correspond to the category assignments suggested by IRIS, corresponding to the inferred central combination of parameter values. This combination is chosen to be relatively central to the set of combinations that respect all the bounds, constraints, and examples (Dias and Mousseau, 2003b). In addition to the assignment of the categories corresponding to the central combination of parameter values, IRIS also infers robust conclusions by indicating the range of assignments in which each alternative might be assigned to (in light green), without violating the constraints, bounds and assignment examples.

When looking at the results of the initial experiment (Figure 5.2, a)), we can see that there are six schools on the second-best category (C^3). Introducing a more restrictive cutting level (i.e., being more exigent with the classification) in the second experiment (Figure 5.2, b)) leads to alternatives *BJA*, *LSB* and *MMV* to be worse classified than previously: *LSB* is now sorted into the worst category (C^1), whereas *BJA* and *MMV* are now sorted into category "Average" (C^2) for the central combination of parameters (weights and cutting level). None of the schools under assessment is assigned to the best category (C^4) for the central combination of parameters. This reveals that these schools should improve their performance according to the standards associated with the reference profiles defining the categories.

It should also be noted that in each of the experiments above the alternative *PBL* cannot be assigned to the category C^2 since it is marked as a black cell. This means that there is no combination of parameters λ, k_j ($j=1,...,12$) allowing for the classification of this school in the category C^2, i.e., when *PBL* is good enough to be better than C^1, it reaches C^3 without being assigned to C^2. On the other hand, it can also be seen in both experiments that the alternative *LSB* can never be classified into C^4.

Using the model with λ ∈ [0.67;1] as a reference, since it is more exigent with the classification, additional preference information was added regarding the constraints on the criterion weights presented in Section 5.5. Initially, the linear constraints to ensure that energy consumption criterion weight (k_1) is always higher than the weight of each of the remaining criteria. Then, the model was parametrized with the constraints where 17 out of 17 experts considered one criterion more or equally important than the other. Afterwards, the remaining constraints were added to complete the set of constraints where at least 16 out of 17 experts considered one criterion more or equally important than the other.

Figure 5.3 presents the results obtained after incorporating the constraints on the criterion weights into the 12 criteria model.



a) Criterion weight constraints (17/17) b) Criterion weight constraints (16/17)

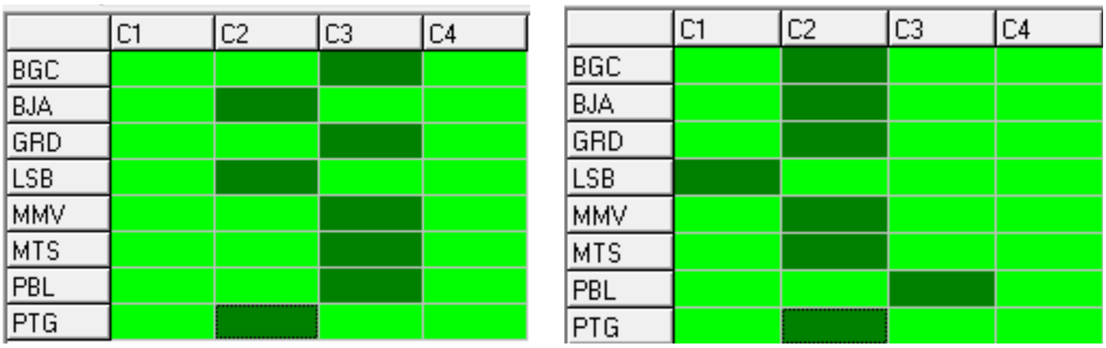
Figure 5.3 – Results including constraints on the criterion weights, λ ∈ [0.67;1] (12 criteria model).

While in the first experiment (Figure 5.2, b)) there is only one alternative (*LSB*) that cannot attain category C^4, when incorporating the DM' preferences there are four alternatives in this situation (*BGC*, *BJA*, *LSB* and *PTG*) (Figure 5.3, a)). On the other hand, when looking to the model incorporating a larger number of constraints on the criterion weights (Figure 5.3, b)), there are six alternatives that cannot attain category C^4 (*BGC, BJA, GRD, LSB, MTS* and *PTG*) which shows that the alternative classification becomes more restrictive as the number of preferences incorporated increases. This is also patent in the classification inferred by IRIS for the central combination of parameters, where there are two alternatives worse classified than previously (*MTS* and *GRD*). *MTS* becomes sorted into the category C^2 with the model with less constraints, and *GRD* was sorted into the category C^2 with the model with more constraints.

PBL still cannot be assigned to the category C^2 since the conditions that make it reaching C^3 without being assigned to C^2 remain the same with the incorporation of the DM' preferences.

5.6.2 Model with 14 criteria

Two additional criteria were added to the model for incorporating the evaluation of societal aspects - the energy awareness of the community (g_{13}) and the contribution for local development related with schools (g_{14}). Therefore, a model considering 14 criteria was used for the sake of comparison with the previously results. Thus, similarly to the experiments performed before, the first experiments with the 14 criteria model were made without including any DM' constraints related to criterion weight preferences, and with the cutting level constrained to the intervals λ ∈ [0.51;1] and λ ∈ [0.67;1]. Figure 5.4 presents the results obtained on these initial experiments.



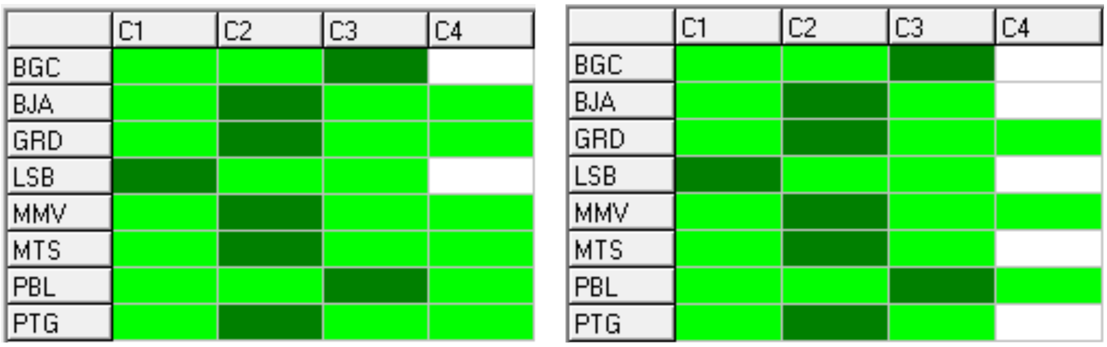
a) λ ∈ [0.51;1] b) λ ∈ [0.67;1]

Figure 5.4 – Initial results (14 criteria model).

Comparing the assignments suggested by IRIS (Figure 5.4), corresponding to the inferred central combination of parameter values, with those obtained for the 12 criteria model, it can be seen that for λ ∈ [0.51;1], only one school (*BJA*) performs worse than before, whereas for λ ∈ [0.67;1] there are three schools performing worse than before (*BGC, GRD* and *MTS*). On the other hand, all the schools under evaluation may be assigned to the complete range of predefined ordered categories (C^1 *to* C^4), without violating any constraint for each of the predefined cutting levels.

With the inclusion of these two additional criteria, not only none of the schools is assigned to the best category (C^4) for the central combination of parameters, but also none of the schools improved its classification. Moreover, there are some schools performing worse than before due to inclusion of societal aspects in the evaluation, since the scores on these criteria were not very good. Thus, it is patent that the schools under evaluation should improve their overall scores according to the requirements associated with the reference profiles defining the categories.

The model with λ ∈ [0.67;1] was used as the reference to incorporate the criteria-weight constraints accordingly to Section 5.5, using the same approach previously followed for the 12 criteria model.



a) Criterion weight constraints (17/17) b) Criterion weight constraints (16/17)

Figure 5.5 – Results including constraints on the criterion weights with λ ∈ [0.67;1] (14 criteria model).

Including the constraints on the criterion weights into the model led the alternative *BGC* to improve its classification for the central combination of parameters. On the other hand, while in the initial experiment using the 14 criteria model (Figure 5.4, b)) the set of schools under evaluation may be assigned to the complete range of predefined ordered categories (C^1 *to* C^4), when incorporating those further DM' preferences there are only two alternatives in this situation (*BGC* and *LSB*) (Figure 5.5, a)). When further constraints on the criterion weights were incorporated (Figure 5.5, b)), the number of alternatives that cannot attain category C^4 increased to five (*BGC*, *BJA, LSB, MTS* and *PTG*). However, this is very similar to what happened to 12 criteria model when a larger number of preference information was incorporated into the model.

5.6.3 Including veto thresholds

Using the model with λ ∈ [0.67;1] with a higher number of weight constraints as the reference (Figure 5.5, b)), an experiment has been performed considering veto thresholds for indoor air quality (g_8) and thermal comfort (g_9) criteria, according to the information presented in Section 5.4. (Figure 5.6).

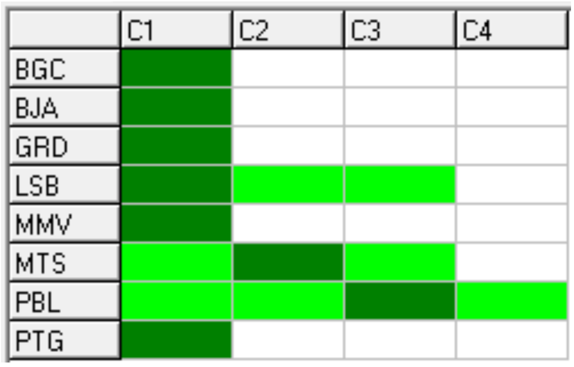


Figure 5.6 – Results considering veto thresholds, λ ∈ [0.67;1], 14 criteria model, criterion weight constraints (16/17).

As it is depicted in Figure 5.6, schools with a score in criterion g_8 lower (since this was a criterion to be maximized) than 50% of accomplishment with the reference value (1250 ppm of indoor CO_2 concentration) were sorted into the category C^1 and could never attain a better category (*BGC*, *BJA*, *GRD* and *PTG*). Similarly, schools with a score in criterion g_9 higher (since this was a criterion to be minimized) than 0.7 were also classified into the category C^1 (*BJA*, *GRD* and *MMV*). Therefore, only three schools from the initial set may be sorted into better categories than C^1.

Indoor air quality and thermal comfort are very crucial in the well-being of school occupants. Therefore, when the score is much worse than the reference value, opposing a veto to the advantages on the remaining criteria may motivate schools to take actions to improve their situation.

5.6.4 Using a classification example

When making an overview of the results inferred by IRIS, it is depicted that school *PBL* had never changed its classification for the central combination of parameters. This alternative is very attractive because it has the lower energy consumption per unit of gross floor area (criterion g_1) and has acceptable levels of indoor air quality and thermal comfort (criteria g_8 *and* g_9). Therefore, the DM may consider that the alternative *PBL* can be used as a reference to others and should be classified as “Very Good” (category C^4) (Figure 5.7).

Action	ELow	EHigh
BGC	1	4
BJA	1	4
GRD	1	4
LSB	1	4
MMV	1	4
MTS	1	4
PBL	4	4
PTG	1	4

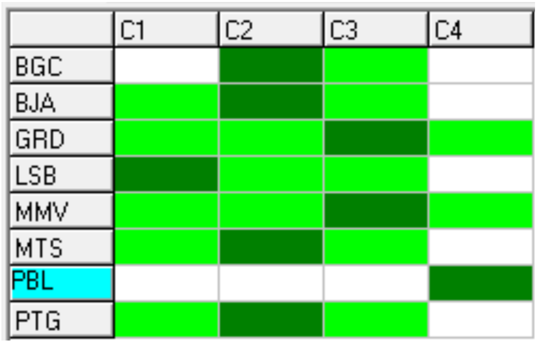


Figure 5.7 – Classification example 1, λ ∈ [0.67;1], 14 criteria, criterion weight constraints (16/17).

Considering as the reference the model with λ ∈ [0.67;1] with the higher number of weight constraints (Figure 5.5, b), when alternative *PBL* was assigned to category C^4, the classification of *BGC* changed from category C^3 to C^2, while the same alternative is no longer sorted into the worst category (C^1). On the other hand, alternatives *GRD* and *MMV* improved their classification to “Good” (category C^3).

However, the DM considers the alternative *LSB* deserve to be in the worst category (C^1) because, besides presenting the higher energy consumption per unit of gross floor area (g_1) and GHG emissions per unit of floor area (g_2), and consequently the higher energy costs (g_5), the water consumption (g_3) and water cost (g_6) per unit of floor area present also the highest values of the entire set of schools (Figure 5.8).

Action	ELow	EHigh
BGC	1	4
BJA	1	4
GRD	1	4
LSB	1	1
MMV	1	4
MTS	1	4
PBL	4	4
PTG	1	4

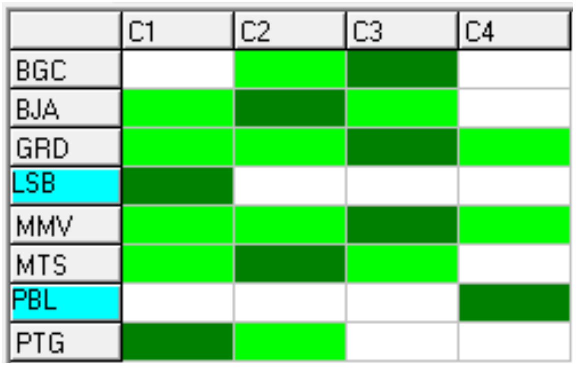


Figure 5.8 – Classification example 2, λ ∈ [0.67;1], 14 criteria, criterion weight constraints (16/17).

The flexibility of the MCDA evaluation model developed and its implementation in the IRIS software enables the DM to proceed with further experiments until being satisfied with the results obtained, e.g., considering that enough information has been gathered, reaching a final classification presenting every alternative sorted into a single category and matching his expert judgments (Figure 5.9), to support a final decision according to the aims and scope of the study.

Action	ELow	EHigh
BGC	3	3
BJA	2	2
GRD	3	4
LSB	1	1
MMV	3	3
MTS	3	4
PBL	4	4
PTG	2	4

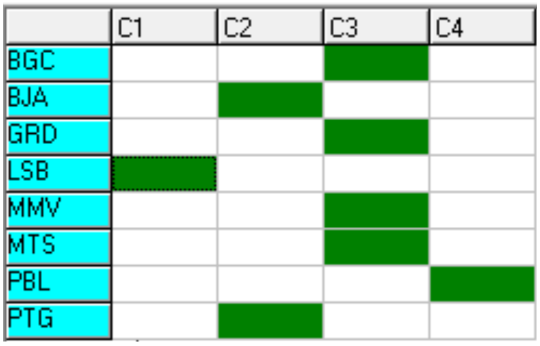


Figure 5.9 – Final classification with examples, λ ∊ [0.67;1], 14 criteria, criterion weight constraints (16/17).

5.7 Concluding remarks

The aim of this chapter was to describe the application of an MCDA model using the ELECTRE TRI method and presenting results obtained with the IRIS DSS.

The chapter started with a summary of the evolution of Portuguese school building stock and a contextualization of the *Secondary School Building Modernisation Programme*. The selection process of the eight schools under evaluation was also described along with the specification of the objectives leading to the criteria of the MCDA sorting model which was then tackled using the ELECTRE TRI method. The performance matrix with the scores obtained for each school (alternatives under evaluation), reference profiles delimiting the categories and the thresholds were also presented. One of the goals of this work was to propose the incorporation of the DM' preferences into the MCDA model. For this purpose, the meaningful definition of constraints on the criterion weights was explored. The chapter ends with a selection of results from the extensive experiments performed.

IRIS indicates for each alternative the category of merit where it is classified according to a set of criteria, providing also interactive ways of progressively reducing the set of accepted combinations of parameter values, until the DM obtain robust conclusions that may end-up with a final recommendation for implementation. Starting with little information and adding only selected pieces of information at each interaction with the DSS allows for a better understanding of their effects on the results. This interactive process has also the advantage of not requiring precisely specified information, thus not being excessively demanding for the DM.

The main contribution of the approach herein proposed lies in the comprehensiveness and versatility of the MCDA sorting model developed and its implementation in the IRIS DSS, thus offering the DM a technically sound and user-friendly approach to gain insights into the problem, learn about the preferences, and make more informed decisions.

Chapter 6 Conclusions and future work

In the final chapter of the thesis, the main contributions of the research developed are presented, the answers to the research questions are summarised and future research topics are outlined.

6.1 Main contributions

Energy consumption in schools is of the utmost importance for providing appropriate indoor environmental conditions, including thermal comfort, indoor air quality and adequate, efficient lighting. Thus, both the environmental burden of energy consumption (derived from generation using fossil fuels) and the increase in energy costs of school buildings are matters of concern. The effectiveness of energy management in schools depends on several technical, operational and management-related factors. As a general rule, there seems to be insufficient awareness on energy performance issues amongst those responsible for the decision-making process in these matters.

This PhD research aimed at gaining a deeper insight on the energy management process in Portuguese school buildings and providing decision support to the school management company, and thus improving the definition of energy policies and energy-related investments. The main purpose of the work was to develop a holistic rating system considering multiple, often conflicting, and incommensurate aspects that influence energy efficiency in school buildings.

A literature review revealed that the energy performance of non-domestic buildings is dependent on several aspects mostly related to occupants and their behaviour, as well as technological issues. For example, this implies that occupants should be able to apprehend the requirements for operating devices in their closest environment easily, and for which interfaces should have adequate readability and provide flexibility of operation while ensuring minimum use of resources, namely energy. Therefore, an interdisciplinary approach addressing the interconnection of people, buildings and technology was necessary to structure an MCDA model capable of rating the energy performance of school buildings considering also non-energy aspects.

The concepts and methods for structuring the complex problems which would then be analysed by multi-criteria methods were reviewed, and the use of SSM and VFT emerged as the methodologies for structuring the problem of multi-criteria energy performance classification of school buildings. The multi-criteria ELECTRE TRI method was deemed to have the most adequate characteristics for the evaluation stage. Moreover, the review found few studies using MCDA methods to perform the evaluation of the energy and sustainability performance of buildings. The most frequent use of MCDA approaches found was related to the evaluation of sets or individual design/retrofit actions to improve the energy and/or sustainability of buildings.

SSM combined with VFT was thus used to unveil the most relevant stakeholders in the energy performance of schools, and the relations among them, and for structuring a set of fundamental objectives for evaluating the performance of school buildings considering multiple, conflicting, and incommensurate aspects influencing energy efficiency in schools.

The selection of the school buildings for evaluation was made in the framework of the 3Es Project. The objectives identified at the structuring stage were converted into criteria whose scores were used to perform the evaluation with the ELECTRE TRI method based on the exploitation of the outranking relation devoted to the sorting problem. The results obtained with DSS IRIS show that MCDA approaches are adequate for evaluating the alternatives and assessing the trade-offs between competing evaluation criteria to enable sounder decisions. The approach followed in this thesis provides the DM with deeper knowledge on the situation under analysis, with preferences being adapted by means of technical parameters and additional constraints until satisfaction with the results obtained, thus leading to more informed decisions.

The research presented in this thesis allowed answering the research questions formulated in the beginning, thus contributing to get a more in-depth knowledge and understanding of energy management issues in school buildings.

RQ 1. Who are the relevant stakeholders, and which are their roles in the energy management process of schools?

Based on a comprehensive literature review, technical visits to schools in different locations in the national territory, multiple discussions with key experts and stakeholders, the use of SSM allowed to identify those who were considered the relevant stakeholders. Chapter 4 presents the approaches followed to explore and structure the relations between the stakeholders identified. The relevant stakeholders identified are international institutions, national government, the school management company, energy supply companies, energy services companies, equipment manufacturers and retailers, facilities management companies, school students and staff, and local community. From the identified stakeholders, the actions of some of them have more impact on the energy management of schools (e.g., school management company, facilities managers, students and staff) than others (e.g., equipment manufacturers, national government, and international institutions), but all of them are interrelated in this process. The rich picture elaborated with the stakeholders considered relevant involved in energy management in school buildings and their roles is a meaningful tool to understand those interrelations.

RQ 2. Which are the most relevant aspects that can have impact on the energy and sustainability performance of school buildings, including non-energy criteria?

There are several relevant aspects with impact on the energy and sustainability performance of schools. From the results of the study, indoor air quality and thermal comfort were considered very relevant since they are directly related to the well-being and health of school occupants. Despite an undeniable improvement in the school buildings, a number of considerations inspired by observation and analysis throughout the several visits at the time emerged, that may be taken both as a description of the present situation and suggestions of improvement.

The first main aspect, and perhaps the most significant, is the need to increase overall awareness on matters related to energy efficiency, thus improving energy literacy amongst all stakeholders. This would also involve an effort to further educate them in matters such as thermal comfort and air quality levels, as well as increasing the amount of aggregated information on end-use energy and resource usage, so that it will be able to provide an input to support decision making.

Another important aspect regards O&M staff, which is in severe shortage in many schools, leading to inadequate operation and equipment deteriorating at an increased pace. On the other hand, O&M would greatly benefit from further education and training in the operation of building equipment and infrastructures, and not just regarding energy efficiency, as some technicians still struggle with basic BACS functions such as adjusting set-point temperatures, ventilation rates, and operation schedules.

Additional work would also be valuable at a higher level, namely at the school managing company and school management boards, leading to the definition of energy policies and energy performance goals, and the creation of a clear framework of responsibility, motivation and incentives in devising energy management activities and implementing energy efficiency measures in school buildings.

RQ 3. How to design a multi-criteria decision aid system for evaluating the energy and sustainability of school buildings incorporating the different stakeholder's preferences and perspectives?

As it was envisaged from the literature review, an interdisciplinary approach addressing the relationships of people, buildings and technology was required to structure an MCDA model for rating school buildings' energy performance considering also non-energy aspects. Therefore, the use of SSM helped to identify the main stakeholders, and their roles and concerns in the process; on the other hand, VFT allowed the structuring of information into objectives to be adapted to criteria in the MCDA model. At this stage, the involvement of students, teachers and support staff was crucial to assess their perspectives. The technical visits and the direct formal and informal conversations and discussions proved to be a key opportunity to explore and gain insight into real-world operation conditions of school buildings across the country, even if some stakeholders did not fully understand the process and terms used.

Concerning the evaluation stage, the ELECTRE TRI was the method used to aggregate the qualitative and quantitative criteria and assign the alternatives into categories of merit. The implementation of the ELECTRE TRI method in the DSS IRIS software allowed dealing with criteria with performances measured in different scales, including qualitative ones, in an effective way. Moreover, this method does not require setting a precise numerical value to express the importance of each criterion, which helps the DM when expressing different preference information interactively and assessing the corresponding impact on the results, thus being a meaningful approach for the DM to gain more insight into the problem until acceptable results are reached.

This MCDA evaluation model can be applied to assess other school buildings and not just those included in this work, since each school is classified based on its absolute merits against the reference profiles delimiting the categories. Also, the model may be used in other typologies of buildings, since preferences defined here may be adapted on a case-by-case basis.

6.2 Future developments

A first step in further developing this work would be extending the present analysis to all schools under the scope of the school managing company, thus improving its decision-making process. Therefore, a platform based on geographical visualization (e.g., geographic information system (GIS)) could be developed where each of the evaluation categories will be assigned to a colour represented on the geographical location of the school. Thus, the company would have access to an overall visualization of school performance updated on a regular time basis (monthly, daily or even near real-time). There could be some flexibility in the relevance and importance attributed to the update timeframe, e.g., some criteria such as energy and water consumption would be updated more often than data for more subjective criteria. Such a platform would also allow for the benchmarking of school performance, allowing the setting of energy targets and objectives that would stimulate improvements on the energy management process, thus contributing to support decision making when defining priorities in investment in energy conservation.

Despite the existence of real-time energy monitoring systems installed in schools, in most cases it is not easy to get accurate and reliable data from it. Thus, it would be crucial to fix and upgrade these systems to operate in appropriate conditions to provide data that would allow end-use/system energy consumption disaggregation. This data would not only be useful to feed platforms such as the one proposed, but also allow for the use of data-driven approaches to forecast energy consumptions and identify anomalous consumption patterns. These approaches would give buildings operators/managers a tool that would enable real-time response/action to prevent unnecessary energy consumption and related cost penalties.

Moreover, (near) real-time reliable and accurate energy data would be also useful to study the cost-effectiveness of implementing demand flexibility actions in future smart-grid operation scenarios integrating large-scale distributed energy generation sources and adoption of electric vehicles.

As an outlook to the future, from a personal point of view, based on the experience of navigating into the world of secondary schools, perhaps the reference for future developments in energy saving strategies in schools would have to be challenging the current growth-oriented economic system towards a collective dawning, leading to change our consumptive behaviours rather than continuously focusing on the technical equipment and building improvement and optimization paradigm. Some of the proposals associated with this may not be the most popular as they go against the (present) flow. For example, “super-size” schools, which have been consistently aggregating large numbers of students from closer-to-home schools that have since been closed, have increased the IEQ needs, leading to a significant use of high energy demanding equipment. Smaller schools would have reduced energy needs, and little or no demand for high levels of active technologies to control and provide indoor comfort conditions, rather relying on passive technologies such as daylight harvesting, natural ventilation and free cooling, and thus energy consumption would naturally decrease, with clear benefits for the pedagogical activities and the well-being of the occupants, adding to reduction of mobility constraints and energy spent in that mobility, since schools could be located nearer to the users.

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