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A Combined Value Focused Thinking-Soft Systems Methodology Approach to Structure Decision Support for Energy Performance Assessment of School Buildings

Hermano Bernardo [1,*], Adélio Gaspar [2] and Carlos Henggeler Antunes [1]

[1] INESC Coimbra, Department of Electrical and Computer Engineering, Polo II, University of Coimbra, 3030-290 Coimbra, Portugal; ch@deec.uc.pt

[2] ADAI, LAETA, Department of Mechanical Engineering, Polo II, University of Coimbra, 3030-788 Coimbra, Portugal; adelio.gaspar@dem.uc.pt

* Correspondence: hbernardo@inescc.pt; Tel.: +351-239-796-327

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Abstract: Several technological, social and organizational factors influence energy management in school buildings, resulting in a complex situation away from the usual engineering approach. The selection of evaluation criteria to assess the energy performance of school buildings remains one of the most challenging aspects since these should accommodate the perspectives of the potential key stakeholders. This paper presents a comprehensive problem structuring approach combining Soft Systems Methodology and Value Focused Thinking to elicit and organize the multiple aspects that influence energy efficiency of school buildings. The main aim of this work is structuring the fundamental objectives to develop a criteria tree to be considered in a multi-criteria classification model to be used by management entities for rating overall energy performance of school buildings. This methodological framework helped grasping the main issues at stake for a thorough energy performance assessment of school buildings and the need to define adequate policies for improvement.

Keywords: energy performance; school buildings; problem structuring methods; soft systems methodology; value focused thinking; multi-criteria decision analysis

1. Introduction

A substantial amount of schools' annual budget for operational costs is devoted to energy bills. Energy consumption in schools is fundamental to provide adequate indoor environmental conditions (air quality, lighting, thermal comfort, etc.) contributing to a proper learning environment [1,2]. Improving energy efficiency in end-use equipment and services is not only an important demand-side resource to reduce energy bills, but also contributes to mitigate climate change by reducing greenhouse gases emissions [3]. Due to the local significance of school buildings, there is also a strong potential to permeate good energy practices in the community.

A major rehabilitation programme—Secondary School Building Modernisation Programme—has been carried out in Portugal since 2007 [4]. This programme was launched as part of a public investment stimulus strategy throughout the country. The analysis of the impact of this programme, namely regarding the operational costs of renovated schools, was the main motivation for the research work presented in this paper, which was carried out in the framework of the R&D project Energy Efficient Schools (E3) [5]. This project focuses on energy consumption and indoor environmental quality.

A wide range of building energy benchmarking methodologies and sustainability certification schemes exist [6]. Energy consumption in school buildings is dependent on many technical, operational and management issues. Therefore, the complexity of the problem of assessing energy performance in this context is not duly captured by usual benchmarking methods based on single energy usage indicators [7].

The use of lifecycle and wider environmental assessment of buildings (e.g., indoor environmental quality, land and water use, sustainability of materials, waste handling, re-use of materials, etc.) has been growing steadily, and various environmental assessment systems for buildings are now in use worldwide [8]. Relevant assessment frameworks of qualitative nature include: Building Research Establishment Environmental Assessment Method (BREEAM) in the United Kingdom; Comprehensive Assessment System for Built Environment Efficiency (CASBEE) in Japan; GBTool in Canada; Leadership in Energy and Environmental Design (LEED) in the United States; and the National Australian Built Environment Rating System (NABERS) in Australia. Some of these assessment frameworks have been adapted for use in other countries [8]. Although those schemes were developed for voluntary application, they have fostered global environmental building performance.

Despite the contribution of the methodologies and certification schemes proposed for increasing the sustainability of built environment, these systems need to be operated by experts. To overcome this barrier, the main purpose of the present work is to develop a holistic sorting 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 indoor environmental quality and even far-reaching issues associated with the involvement of community regarding the dissemination of good practices.

The decision context is inherently unstructured with multiple stakeholders with potentially conflicting perspectives and interests. According to the authors' experience in energy planning problems, the use of Problem Structuring Methods (PSM) offers a valuable analytical framework for unveiling and structuring the relevant evaluation aspects. The Value Focused Thinking (VFT) approach is then used to refine these aspects as objectives to be included in a Multi-Criteria Decision Aid (MCDA) model, which is aimed at classifying the energy performance of school buildings taking also into consideration further non-energy effects. Similar approaches were followed in the context of sustainable urban energy planning [9], analysis of energy efficiency measures [10], energy behaviour modelling [11] and also within the European Union-funded project "Systems Thinking for Energy Efficient Planning (STEEP)" for developing energy master plans for districts in three European cities [12,13]. A taxonomy of the endogenous and exogenous variables of MCDA tools was formulated with the aim of selecting the appropriate method for evaluating design proposals of a new office building in Rome [14].

The work presented in this paper bridges the human-centred and technical-centred perspectives regarding the assessment of energy efficiency in school buildings. The use of a combined approach coupling a PSM ("human-centred") with VFT to structure the decision criteria to be used in an MCDA model helped to better understand a complex situation and the role and importance of each stakeholder in the process, as well as the relationships between them. Similar approaches have been followed to understand the decision making process in the context of complex situations related to sustainable renovation of buildings [15] and construction of low-energy buildings [16].

The paper is divided in six sections. This section provides the motivation and framework of the study. In Section 2, a brief overview of PSM and Soft Systems Methodology (SSM) is presented. Section 3 presents the application of SSM for energy performance assessment of school buildings. The results of the problem structuring leading to the tree of fundamental criteria using the concepts of VFT are presented in Section 4. A discussion about the main findings is carried out in Section 5. Finally, conclusions and an outlook of further research work are presented in Section 6.

2. Problem Structuring Methods and Soft Systems Methodology

Operational research (OR) models and methods aim at helping decision-makers with complex decisions, where the alternative courses of action can be implicitly defined by a set of restrictions in a mathematical model or explicitly known at the outset. The merit of the feasible solutions is assessed by single or multiple objective functions or criteria. Often multiple, conflicting criteria are at stake, which requires the incorporation of the values and preferences of the stakeholders in the decision support process. These unstructured and complex problem situations make traditional OR mathematical modelling tools less effective.

Unstructured or ill-defined problem situations generally involve stakeholders with potentially 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 [17]. Unstructured problems are outlined by the existence of multiple stakeholders, perspectives, conflicting and/or incommensurable interests, with intangible issues and important uncertainties [18].

Over the last forty years, new approaches have been developed to deal with this type of problems away from traditional, mathematically-based tools of OR. Those methods are based on qualitative and often diagrammatic modelling procedures. Thus, they are not mathematical, but they are nevertheless structured and rigorous. Together, these methods form what is established as Soft OR or PSM [17].

Soft OR approaches aim to help groups of stakeholders gain a comprehensive knowledge of a problematic situation of common interest, which is generally characterized by high levels of complexity, uncertainty and conflict. Modelling and facilitation are used to 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. To achieve this main purpose, PSM must: enable bringing into discussion multiple perspectives; developing a representation that can inform a participative process of problem structuring, which should be cognitively accessible to stakeholders with different backgrounds and without specialized training; adjusting the problem representation to reflect the state and stage of discussion among the stakeholders in an iterative manner; and allowing partial improvements to be recognised and committed to, instead of requiring a global solution.

Several PSM have been proposed to deal with unstructured and complex problem situations. Rosenhead summarized a set of PSM in reference textbooks in the field [18,19]. The most used are: Strategic Options Development Analysis, Soft Systems Methodology, Strategic Choice Approach, Robustness Analysis and Drama Theory [20].

The option for using SSM in the structuring process to develop a decision support tool for assessing energy performance of school buildings has been due to authors' familiarity with systems language in face of their background on engineering and control systems. Within the context of decision making processes, SSM has also been used as a starting point to problem structuring for developing MCDA models [21,22].

The main purpose of SSM 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 [23]. 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 [24]. SSM represents a different epistemology with regard to traditional systems engineering, in that it is claimed that the system should not be viewed as some part of the world that 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 [25].

The SSM approach consists in an inquiry process with seven stages, which leads to a learning and understanding system of the problematic situation under study [23,26]. In this process, there are five stages associated with the so called "real-world", two of them for understanding and defining the problem situation, and the other three for deriving change recommendations and taking actions to improve the problem situation, based on a comparison of models and the "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 researchers in different countries. An updated description of SSM is given below based on the experience of the worldwide application to several situations [27]. This formulation is the one normally used and defines SSM only based on four main activities [26]:

1. Finding out about a problem 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 that would improve the situation and are regarded as both 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 1 outlines the cyclic nature of the methodology.

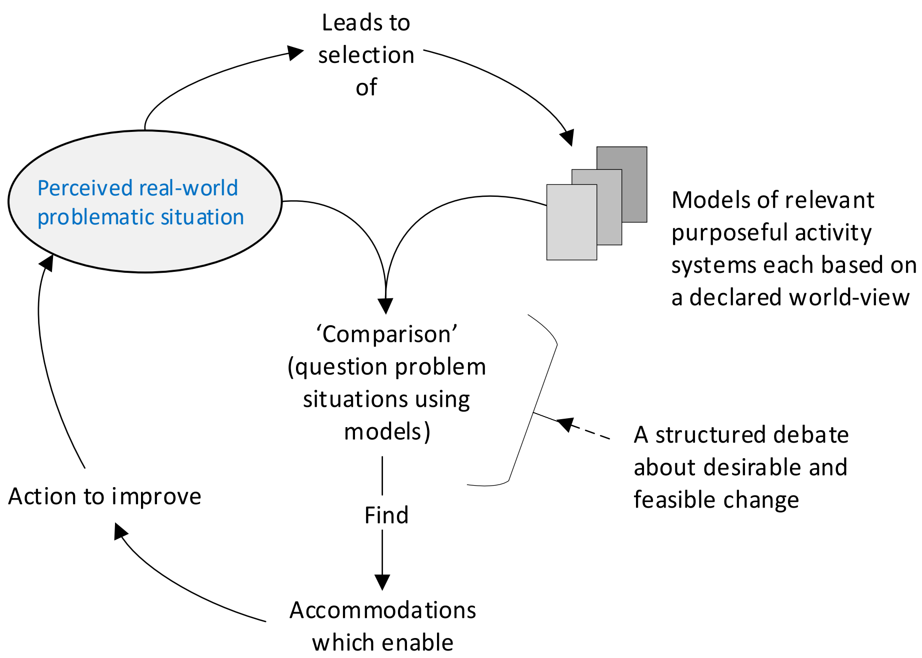

Figure 1. The inquiring/learning cycle of SSM [26].

3. Methods: Using SSM for Energy Performance Assessment of School Buildings

The implementation of SSM to a problematic situation requires collecting as much data as possible to make its representation. Four ways of finding out about a problematic situation become a usual component of SSM application [24]. These ways are known as "making Rich Pictures" and involve three kinds of inquiry: "Analyses One, Two and Three". The application of SSM to assess energy performance of school buildings is presented in the following sub-sections.

3.1. Identification of Stakeholders

Drawing a *rich picture* is one of the most widely known devices of SSM to represent the elements in the problematic situation. Its purpose is to represent visually the structures, processes, stakeholders, relationships, culture, conflicts, issues, etc. [26].

In Figure 2, the rich picture aimed at representing the situation under analysis in this paper is shown. This diagram was built using information in the scientific literature on methods used for assessing energy performance of buildings, technical visits to eight Portuguese schools in different climatic regions, and discussions with experts from the University of Coimbra, the R&D Institute INESC Coimbra, the schools management company, facilities management companies, equipment manufacturers and retailers, members of the board of directors of schools, students, and members of the parents associations.

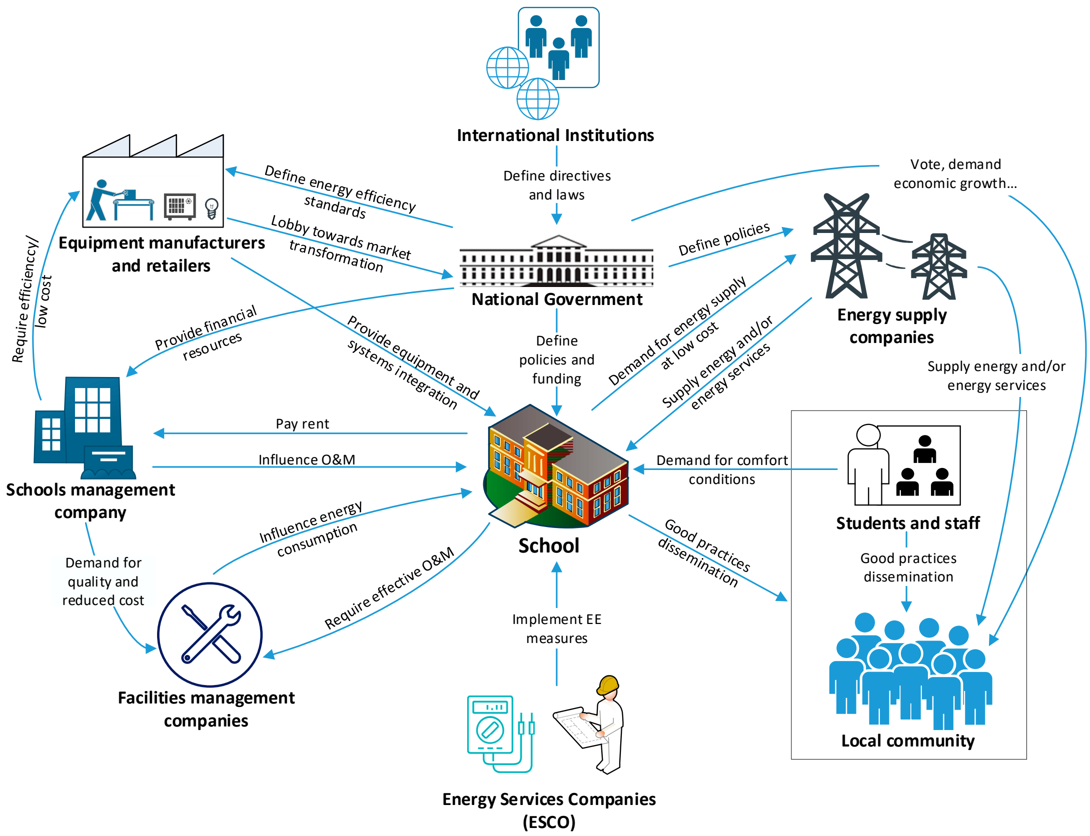

Figure 2. Rich picture of stakeholders involved in school buildings energy management.

The rich picture was complemented with the inquiry process named Analyses One, Two and Three [23,24,27], which focus on the intervention itself, a social analysis and a political analysis, respectively. This helped to grasp the problem situation as comprehensively as possible. The main 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 greenhouse gases 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 the modernisation programme.

Schools management company is responsible for planning, managing, developing and implementing the 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 with capability to take a commercial approach to managing the procurement and maintenance. It is funded from 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 [4]. 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 ESCO.

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 on a scenario of a widespread development of smart grids and smart energy management devices.

Energy services companies (ESCO) 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 in 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 [28], 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 Building Management and Control System (BMCS) 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, operation and maintenance, with the aim of supporting and improving the effectiveness of building's facilities and infrastructures. Effective facilities management 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. In this study, the operation and maintenance of facility's equipment and systems may influence significantly the overall energy performance of each school. They are required to deliver quality of service at competitive costs.

School represents 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 its lack) 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 an impact on public opinion and local community because these 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 indoor environmental conditions.

In this framework, the following considerations emerged from the analysis throughout the several visits to school buildings:

- It is required that the school management company along with the management boards of schools define energy policies and set goals related to energy efficiency.
- There is no responsibility framework for the effective implementation of the energy management activities, both at school management company and at school level.
- There is a lack of clear line of authority and responsibility for the implementation of energy conservation measures.
- There is a lack of awareness of energy conservation issues amongst some stakeholders, such as students and staff and even in the management board of some schools.
- In general, the operation and maintenance staff shows a lack of education and training for the effective operation of building's equipment and infrastructures. This was observed not only in terms of energy efficiency related operation, but also at all operation levels of equipment and systems, e.g., in the case of BMCS, some technicians do not know how to change set-point temperatures, ventilation rates, schedules of operations, etc.
- Although the technical facilities are complex and have a vast amount of automatically controlled equipment, it was verified that in some schools there is no operation and maintenance staff or, where it exists, the number of technicians was insufficient, which leads to the increase of the pace of the deterioration process of equipment and systems, sometimes due to an inadequate operation.
- There is a lack of aggregated information about end-use energy and resources usage to support decision making.
- There is a lack of an effective knowledge of the general comfort levels required by the building occupants.
- There is no clear framework to motivate and incentivize the implementation of energy efficiency measures in school buildings.

3.2. Root Definition

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. 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. The transformation (T) is accompanied by another important SSM concept, the *Weltanschauung* (W) or worldview.

The first approach for improving the situation is to develop a system to understand, manage and help to continuously improve energy efficiency and indoor environmental quality 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, in order 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 a guidance for establishing root definitions, the CATWOE elements were proposed 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) [23]. Together, T and W are the core elements of CATWOE analysis.

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 [29]. Table 1 presents these questions, along with the CATWOE mnemonic definitions for the situation under analysis.

Table 1. The elements of a CATWOE and their root definition.

Mnemonic	Terms	Questions	Root Definition
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)	Understand the energy performance of schools, leading to the improvement of energy management and definition of energy policies and energy related investments.
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 preferences of the stakeholders.
O	Owner	Who can stop or change the T?	Schools 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 existing planning and operation; Funding and technological constraints; Legislation and directives.

3.3. Conceptual Model

After completing the root definition, 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 [23]. To build the conceptual model, it is recommended to use 7 ± 2 activities, excluding monitoring and control activities, based on [30] which suggested that the human brain may have the capacity to cope with around seven concepts simultaneously.

The conceptual model developed for the classification of school buildings into categories of performance is shown in Figure 3.

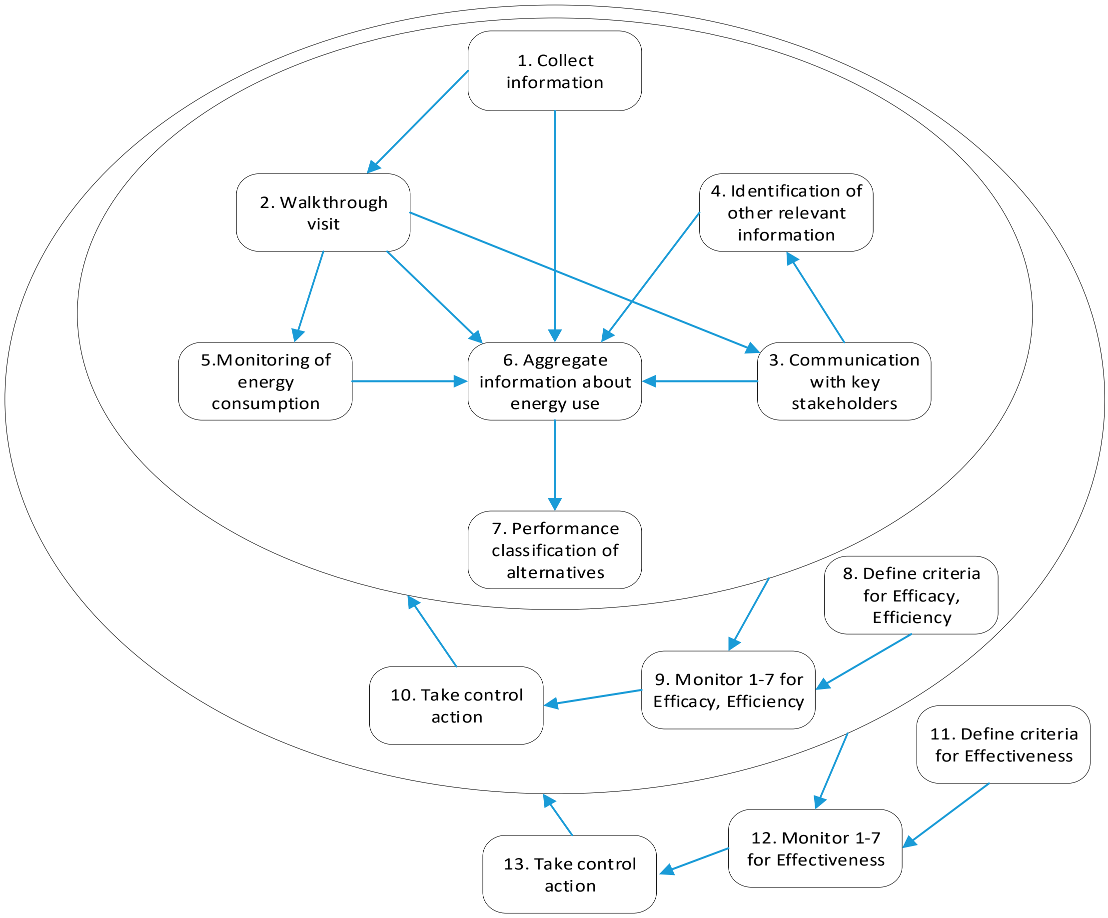

Figure 3. Conceptual model of the classification system.

Activity One 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 (heating, ventilation and air conditioning - HVAC, pumps, lighting, domestic hot water, etc.). This information enabled to identify the main topics to be clarified during the on-site visit.

Activity Two 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 Three 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 Four, regarding identifying and collecting other relevant information for the classification process.

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

Activity Six 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 objectives [31] 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 Seven, 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 Decision Maker and other stakeholders into the decision support process [31]. The structuring of fundamental objectives is presented in Section 4.

The conceptual model should incorporate the processes of monitoring and control, which establish measures of performance. Monitoring and control were described in terms of efficacy, efficiency and effectiveness ("3Es") [26]. 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. 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 is 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 schools' 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 are used as reference for others' improvement. To achieve effectiveness, an energy management scheme focused on continuous improvement strategies should be implemented so that the savings remain over time.

3.4. Comparison and Debate

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 the root definition [23]. Four ways of doing the comparison were described: 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 [23]. Of these, formal questioning has emerged as by far the most common [26]. Structure to the discussion is provided by using models as a source of questions about the situation [24].

In the present study, 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 [32], 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. The present study focused on performing a demand-side analysis of the buildings energy consumption. Therefore, instead of primary energy, final energy consumption is 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 on non-energy aspects in the evaluation system. In 2014, the International Energy Agency 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 [33].

Moreover, the project "COMBI—Calculating and Operationalizing the Multiple Benefits of Energy Efficiency in Europe" has been recently funded by the European Union's Horizon 2020 research and innovation programme [34]. 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 the present 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 [35,36]. In schools, a 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 BMCS to keep the HVAC systems active only during a limited time of the occupancy period, leading to measured 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. The authors performed a simulation study of one of the schools analysed, where it is shown that it is possible to extend the usage of mechanical ventilation according to the required enhancement of indoor air quality. This action in conjunction with the adoption of new lower fresh air flow rates would improve air quality while avoiding excessive cost and without requiring any investment [37].

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

4. Results: Structuring the Fundamental Objectives

The SSM approach presented above, 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 [31] were used to elicit and structure objectives (or points of view of the decision makers) 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. Fundamental objectives concern the ends that decision makers value in a specific decision context; means-objectives are ways to achieve ends [31]. 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. The interrelated values about the same fundamental concerns were grouped into categories, which are associated with fundamental aspects for assessing the energy efficiency 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 [38]. In this work, the methodology proposed in [38] 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.

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. These reductions could also be achieved through the use of renewable energy sources, which should be used in addition to the implementation of demand-side energy efficiency measures. Any energy efficiency measure taken should have direct impact on the energy consumption of the building. 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 the amount of 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 a 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 greenhouse gases 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 lead to environmental benefits but can also contribute to decrease the energy consumption (and related greenhouse gas 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 greenhouse gases that impact global warming related to energy purchased by the school. It depends on the carbon intensity of the country's mix since it is calculated as 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. 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 operation and maintenance 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 energy consumption of the school. 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. 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 [39].
- *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) [40], 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 acoustic performance of the buildings. The performance in this criterion is 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 a qualitative criterion.

Objective 6: to improve school's maintenance efficiency. 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 BMCS 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. The technical maintenance staff engagement and training focused on energy efficiency, together with a lifetime commissioning approach to BMCS, 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.
- *BMCS performance*: It accounts for the knowledge and perception of the technical operators about the performance of BMCS. The nature of this criterion suggests it should be assessed on a qualitative basis.

The final aim of the work presented in this paper was to structure the objectives that emerged into a hierarchy. Figure 4 shows the resulting tree of objectives.

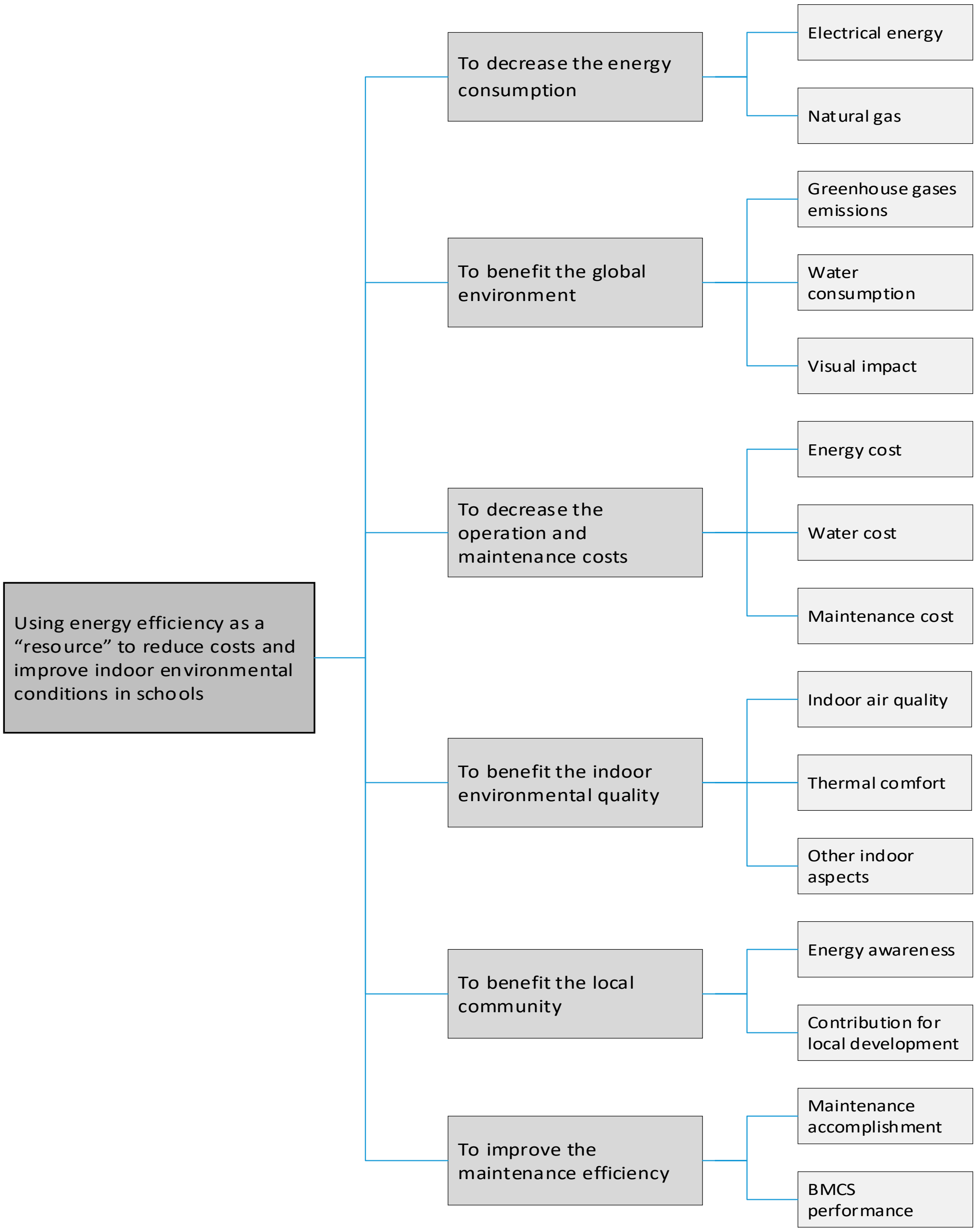

Figure 4. Structured tree of fundamental objectives.

5. Discussion

According to [31], 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. When looking to 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 also for greenhouse gases emissions). Nevertheless, authors thought about it for improving the clearness of the process, avoiding neglecting some concerns and different perspectives of the different stakeholders involved.

Structuring a functional value hierarchy into a criteria tree can be carried out using two classical approaches: top-down or bottom-up [31,38,41,42]. 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 to be missed.

In this work, a combination of top-down and bottom-up approaches was followed. Initially, a bottom-up approach was performed to identify a set of fundamental objectives. Then, a top-down approach aimed at breaking down each objective into sub-objectives clarifying the essential issues to performance measurement in each objective.

In the future, the tree of fundamental objectives presented above will be converted into criteria to be used in the multi-criteria decision aid model. During the structuring stage, the multi-criteria ELECTRE TRI method was considered having 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. Reference profiles, which define the boundaries of the categories, are used to sort each alternative. This method enables incorporating the decision maker'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 [43–46].

6. Conclusions and Outlook

A methodological approach combining SSM and VFT has been developed for supporting the structuring of an MCDA model to evaluate the energy efficiency of school buildings incorporating energy and non-energy aspects. Improving energy management in schools has a strong potential for reducing the overall costs, while also enhancing the conditions for improving educational quality.

The first stage consisted in the identification of the main stakeholders and their roles and concerns in the process of improving energy efficiency of school buildings. The resulting rich picture enabled to elicit information from stakeholders to refine it and hence the holistic view of the situation, which also contributed to understanding its social and cultural features.

Using SSM for problem structuring was a challenge that brings to discussion the main issues that should be addressed during the assessment stage. The insights of the experts were useful to identify a set of fundamental objectives. Then, those insights were structured in a criteria tree to perform the evaluation of the alternatives. The use of the VFT approach revealed to be a useful tool for structuring the objectives and values of the decision makers to design the multi-criteria evaluation model.

The involvement of students, teachers and support staff was crucial to assess their own perspectives on energy performance and operational costs. These stakeholders are also key elements to help raising awareness and gain support from the local community in developing energy efficiency actions.

Despite the flexibility on application of SSM, some difficulties emerged when it was required to perform discussions and debate about the conceptual model and to elicit the objectives. Some stakeholders revealed misunderstandings about the process and terms used, which increased when it comes to values more difficult to define, leading sometimes to deviations from the main conversation topic. Nevertheless, those meetings were useful for authors to gain a deeper understanding about alternative ways on how to conduct such a consultation process and how to better explain the process to stakeholders.

Work is currently underway using ELECTRE TRI to deal with the criteria tree herein developed to assess the energy efficiency performance of a selected set of school buildings. The final outcome will be having the school buildings under appraisal sorted into ordered categories of merit according to their performance in the multiple evaluation criteria. This information is relevant for grasping the results of the modernisation programme as well as assist shaping policies for future interventions in school buildings.

The evaluation model could be adapted to be used in other types of buildings, according to the decision maker's needs and preferences.

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