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Performance study of a multi-objective mathematical programming modelling approach for energy decision-making in buildings

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ABSTRACT

The improvement of energy efficiency in buildings is among the first priorities worldwide. To this end, several measures are available, and the decision maker faces a decision problem with multiple objectives having to compensate several energy, financial, and other factors in order to make a satisfactory selection. To solve this problem, a decision modelling approach is proposed herein, based upon the principles of multi-objective mathematical programming, thus capturing only these elements, which affect the decisions to be taken. To evaluate its performance under realistic operational conditions in a building, the proposed approach is applied to an existing building for retrofit purposes, and several simulation investigations are performed in order to study and evaluate the quality of the retrofit alternatives proposed by the decision model. The results of these simulation investigations confirm, that despite its reduced precision compared to the corresponding simulation model of the building, the decision model allows for the realistic comparative evaluation of the considered alternatives. The example case study reported herein, demonstrates also the functionality of the proposed approach, exploits its qualities, and highlights its strengths, weaknesses and limitations.

1. Introduction

The energy sector nowadays faces significant challenges that are expected to become even more acute in the upcoming period. The current energy trends as well as the related carbon emissions raise great concerns about the "three Es", i.e. the environment, the energy security and the economic prosperity as defined by the IEA (International Energy Agency) [1]. Improving the energy performance of buildings is a key measure to achieve the ambitions of Europe, particularly EU Climate & Energy targets to reduce Greenhouse gases emissions by 20% and achieve energy savings of 20%, both by 2020. Being responsible for the 40% of the energy consumption and 36% of the carbon emissions worldwide, buildings are targeted as the sector with the most significant energy efficiency margin. Energy efficient economy should be the main focus in the buildings and construction sector as mentioned in the 2012/27/EU directive announced in October 2012 [2]. In order to shift to a more sustainable future, the spread of innovative technological solutions should be accelerated.

From the energy perspective, the adaptation of buildings in the climate change involves solutions considering the building envelope and its insulation, the space heating and cooling systems, the water heating systems, the lighting appliances and other equipment. In contrast, however, to other systems, most buildings have a long life span. This means that more than half of the current global building stock will still be standing in 2050, while, at the same time, even new buildings under the present economic environment can be energy inefficient [3,4]. As a consequence, most of the energy and CO_2 savings' potential lies in the retrofitting and procurement of new technologies for the existing building stock, as well as in the efficient design and establishment of improved standards for new buildings. To this end, various measures may be considered in the design but also in the operational stage of a building, when renovation or retrofit actions are performed [5].

According to Wulfinghoff [6], there are over 400 alternative measures which may be considered separately or combined in groups. With such a variety of available measures, the main challenge is to identify those that will be the most effective and reliable in the long term considering environmental, energy, financial or other factors. In other words, the DM (decision maker), who may be the architect, the engineer or the building expert, faces a decision problem with multiple objectives, where the search of an optimal

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solution is meaningless, since the criteria, which have to be satisfied are generally competitive (e.g. energy efficient solutions are more expensive than less efficient ones).

The dominant approach to the aforementioned problem involves, mainly, simulation-based approaches, whereby alternative scenarios, which are expected to improve the energy performance of the building under study, are initially prescribed by the DM [7]. These specific scenarios, which may vary according to buildings' characteristics, type, use, climatic conditions, etc., are then evaluated through simulation using more or less advanced/detailed calculations [8–18]. Sometimes, the DM employs complementary to simulation, advanced decision support techniques. This procedure may involve for example multicriteria-based decision making methods (see e.g. [19–26]) that are introduced to assist him/her in examining the trade-offs among the pre-defined and pre-evaluated alternative actions and reach a final decision (see Ref. [27] for a complete state-of-the art review).

The approach described above allows the DM to obtain a quite precise quantification of the alternative scenarios and solutions' energy performance. Moreover, this approach requires advanced knowledge and expertise from the DM in order to successfully select the predefined energy efficiency scenarios, solutions and technologies. Therefore, in the simulation based approach the decision problem is discretised, and some of the resulting discrete solutions and scenarios are examined. As a consequence the optimality of the final solution depends in a great extent on the DM's ability and expertise as well as on the number of the examined discrete solutions. For example, if the DM decides to evaluate only a small number of solutions, the optimality of the final solution is not at all guaranteed. In fact, there is no guarantee that the final solution is among the set of good solutions, in the sense that there might be other energy efficient ones that perform better in all the considered criteria. Furthermore, the selection of a representative set of alternatives is usually a difficult problem, while the final solution is heavily affected by these predefined alternatives. On the opposite case, i.e. if the DM defines a large number of solutions, the required evaluation and selection process may become extremely time-consuming and difficult to handle. As a consequence, the DM's work is limited to a potentially large but certainly finite number of alternative scenarios, while the real opportunities are enormous.

In order to avoid the predefinition of the alternative scenarios and/or solutions that will be evaluated, various alternative approaches have been proposed. In one of these approaches the decision problem is defined considering multiple objectives, while energy simulation models are combined with GAs (genetic algorithms). The recent literature reports on several such approaches (see Ref. [28] for a complete relevant review), where GAs are combined with known tools like the DOE 2.1 [29] thermal analysis software [30–32], the TRNSYS [33] simulation software [34,35], or other less known energy calculation models [36–43].

In all these approaches, GAs are employed to search the decision space, while the simulation or other energy analysis tools are used to evaluate the solutions proposed by the GAs. This approach however, is still computationally expensive, since the time associated with optimisation can become prohibitively high due to the usually large number of simulations that need to be performed. Nevertheless, the DM has the ability to examine a potentially infinite solution space, while obtaining at the same time a quite precise quantitative evaluation of the examined solutions. By nature, the GAs may provide also several satisfactory solutions, as they result in a population of good solutions rather than a single solution, while they allow the utilisation of quite complex mathematical models.

The necessity of applying GAs is justified by the size and the complexity of the defined optimisation problems. The usage, however, of the simulation or the other employed tools may considerably increase the computational effort, which is already overloaded due to the requirements of developing and running the GA itself. In addition, the GAs do not guarantee the finding of the optimal solution, while in the majority of the cases reported in the literature, the DM's preferences are not taken into account during the decision making process [28]. Instead, the GA is limited in finding the Pareto frontier, i.e. the set of solutions that are not dominated by any other solution. This means, however, that other more or less sophisticated techniques have then to be applied upon it, in order to identify this single solution that will satisfy the DM's preferences. On the other hand, a multi-objective methodology can be developed without any need of coupling with other tools, based on a mathematical programming rather than a building simulation type of modelling.

According to Williams [44], a mathematical programming model involves a set of mathematical relationships such as equations and inequalities, which correspond to some down-to-earth relationships in the real world. In many occasions, the data utilised to build such models are not precisely quantified and the developed mathematical relationships do not reflect all the real-world problem details. Nevertheless, with mathematical programming, it is still possible to result in little inaccuracies in the solutions, if the elements of reality that are important in decision making are captured. After all, within the context of decision making, the purpose of mathematical programming models is not to precisely represent reality but to assist the whole process through the creation of a realistic basis for the comparative evaluation of the available alternative solutions at the less possible computational effort. For this reason, such models should be used as one of a number of tools for decision making, and the answers that they produce should be always subjected to close scrutiny [44].

Following the mathematical programming type of modelling, Diakaki et al. [5] investigated and developed [45] a multi-objective decision modelling approach for the problem of energy efficiency in buildings, which has then been adopted by other researchers too (see e.g. [46–49]). It is the aim of the present study to further investigate and highlight the strengths, weaknesses and limitations of the specific approach, as well as its potential synergies with other methods, within the context of decision analysis for the energy efficiency in buildings. To this end, a decision problem concerning the retrofit of an existing building is defined. The problem is modelled as a multi-objective mathematical programming problem and solved via available relevant solution techniques. The suggestions of the decision model are then evaluated under real operational conditions using a validated simulation model of the building, while useful results and recommendations are extracted. It should be noted here that the focus of this particular study is not on the specific decision problem addressed herein, but on the methodological approaches, which may be adopted for its solution.

The rest of the paper is structured in five more sections. Section 2 introduces the considered retrofit decision problem, while Section 3 presents its solution via the proposed multi-objective mathematical programming approach. The simulation evaluation of the decision model's recommendations is presented in Section 4, while a discussion of the findings of the study, as well as of the strengths, weaknesses and limitations of the proposed approach follows in Section 5. Section 6, finally, summarises the conclusions of the study.

2. The decision problem

The decision problem considered herein focuses on the energy efficiency of the building depicted in Fig. 1. The specific building is located in the suburbs of Iraklion, Greece within the campus of TEIC