Energy Efficiency Improvement of Buildings by Using Linear Programming

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Abstract

Energy efficiency is an important issue. Innovative technologies are developed in order to make buildings better at energy efficiency. Energy efficiency labels are used around the world to show how much energy efficient a building is. This labelling process is an assignment of buildings into predefined classes. If we consider the assignment problem has multiple criteria to consider and the classes are ordered, this problem can be handled by using multiple criteria sorting techniques. Furthermore, Inverse Multiple Criteria Sorting Problem (IMSCP) is concerned with the selection among the possible actions, which can change objects state in terms of criteria to obtain a better sorting of objects. In this study, a linear programming model of IMSCP is proposed to construct an energy efficiency improvement plan for buildings. The main aim is to choose the actions, which give us the desired labels at minimum cost. An illustrative example is presented to demonstrate the applicability of the proposed model. Solution results prove that this model is appropriate for energy efficiency improvement of buildings.

Keywords: Building energy efficiency, Inverse multiple criteria sorting problem, Linear programming.

1. Introduction

Buildings are primary users of energy and energy efficiency of buildings is important in many countries. It is important to use energy efficiently, because of the limited global energy resources and the harmful effects of fossil fuels (coal, oil, etc.) on energy generation to the environment. There is a great potential to save energy in the building sector.

The heating, ventilation and air conditioning (HVAC) systems in the buildings provide the comfort, health and safety of the residents. Generally, these systems are the most important energy consumers. Their design is shaped by the architectural characteristics of the building and the needs of living. While HVAC systems provide and maintain energy efficiency, they must be designed to be modified for future needs.

Today, building energy design often needs analytical power to study complex design scenarios. Computer based building energy simulations provide this power and allow for great flexibility in the design process. The simulation method is based on load and energy calculations in HVAC designs. The aim is to identify and study the energy characteristics of buildings and systems.

Design alternatives are need to be in harmony in terms of initial investment, maintenance and energy costs. Fortunately, simulation techniques provide tools to create different design options based on energy performance and lifetime costs.

When there is a consideration about energy performance which is related to the evaluation of the building performance, it is necessary to define the energy efficiency based on the criteria on which the building is to be defined, standards definition, regulations and guidelines. Within the framework of the energy efficient building concept, each country has its own standards, regulations and directives which is developed within its own local conditions.

Building energy regulations and standards will help to recognize the energy conservation potential in buildings and increase the demand for energy efficient design in buildings. This will also provide a basis for the development of energy efficient policies.

Building energy regulations and standards are being used and developed in many countries to ensure a certain level of control over building design and the development and renewal of energy-conscious design in buildings.

In the last decade, Turkish Government are developing similar regulations with European Union (EU) and new standards and regulations for energy saving and renewable energy sources usage are being published.

The most important of these legal regulations is the "Energy Performance in Buildings (BEP) Regulation" which abrogates the "Regulation on Thermal Insulation in Buildings" from the implementation date. In accordance with the framework directive 2002/91 / EC of the European Union, the Regulation on Energy Performance in Buildings was published in the Official Gazette on 05 December 2008 and entered into force on 05 December 2009.

One requirement of this regulation is to prepare an "Energy Identity Certificate" for each building. The Building Energy Performance Calculation Method to be used in the preparation of the Energy Identity Certificate is a method of calculating the energy efficiency of buildings by evaluating all the parameters affecting the energy consumption of the building in accordance with the regulations such as houses, offices, education buildings, health buildings, was designed to assess energy performance for all existing and new building types.

According to the energy performance in the Energy Identity Certificate, buildings are assigned to energy classes from A to G. A is the highest, G is the lowest energy-efficient building. According to the relevant legislation, the energy identity certificate class of the new buildings must be designed and built to be at least C class. Buildings that are lower than class C will not receive a residential usage licence. In addition, energy pricing and taxation will be done according to the determined energy class. In other words, high energy class buildings will buy energy at a lower price. For this reason, energy performance will be the reason for preference in purchasing, selling and renting. The value of buildings with high energy class will increase.

In this study, the problem of determining the actions that can be taken to improve the energy classes of buildings identified in the Energy Identity Certificate is modelled as the Inverse Multi-Criteria Sorting Problem, which is proposed by Mousseau et. al (2017). The choice of improvement options for energy efficiency is done by the proposed linear programming model.

This paper goes on as follows. A summary of recent literature on energy efficiency improvement studies is presented in the second part. In the third part, the proposed linear programming model to improve energy efficiency is defined by giving parameters and mathematical formulation. In the fourth part, the applicability of the proposed model is tested on an example of energy efficiency improvement. The study is concluded in the fifth part by giving the results and the research directions for further studies.

2. Literature Review

The use of multi-criteria decision-making approaches in measuring and improving building energy efficiency is one of the popular topics discussed by researchers in recent years. Some of the following are summarized below:

Diakaki et al. (2010) aimed to improve the energy efficiency of buildings in the design phase with a multi-objective optimization model that includes the structure of the building and the decision variables that express the energy system used. In the proposed model, it is aimed to find the building design parameters that minimize the maximum proportional deviation from the building energy consumption, CO_2 gas release and initial investment cost.

Wang et al. (2012) examined quantitative energy performance assessment methods for existing buildings. It is stated that energy performance evaluation methods in the study can be examined in three topics as calculation-based, measurement-based and hybrid methods.

Kabak et al. (2014) determined energy classes of three buildings by using building energy performance measuring system in Turkey based on 7 criteria which can be expressed with linguistic variables and interacting with each other. Fuzzy Analytic Network Process method is used for evaluation of buildings and the obtained results are compared with Analytic Hierarchy Process and TOPSIS methods.

Hu et al. (2015) evaluated energy performance based on 6 criteria for three parts of a building on the Wuhan University campus. The result obtained by Fuzzy Analytical Network Process in this study are being used for interpretations in terms of future improvements of campus buildings.

Xu et al. (2015) used the Fuzzy Analytical Network Process method to determine the importance of effective criteria for sustainable improvement of the energy performance of hotel buildings in China. The results of the decision model in which inter-criteria interactions are taken into account show which factors are more effective in improving performance.

Delgarm et al. (2016) proposed a three-objective optimization model that optimize building energy performance for four different climatic regions in Iran in terms of cooling, heating and energy consumed in lighting. To obtain quick and good solutions for the proposed model, a Multi-Objective Particle Swarm Optimization based solution approach is developed.

Ignatius et al. (2016) stated that sustainability is one of the most important concerns in construction projects, and they have implemented green building evaluation in Malaysia with a Quality Function Deployment and Fuzzy Analytical Network Process-based approach. In a sensitivity analysis that observes the effect of changing the weight value is used to defuzzification of the fuzzy results, the changes of different decision makers are examined.

Migilinskas et al. (2016) developed an ARAS-based assessment approach from multi-criteria decision-making approaches to assess building energy performance. The study, which considers the economic, technical and environmental criteria, show that the energy performance of the building is not directly proportional to the investment amount, so the additional expenditure has no effect on the building energy performance.

Jeong et al. (2017) proposed a modified system of the BECC system used to assess the energy performance of existing buildings in South Korea against possible problems with respect to criteria and evaluation criteria. By using the recommended system and the K-means clustering method, they obtained improvements in classifying the energy performance of 504 buildings.

According to the literature, it seems that optimization studies have not been used to improve the energy performance of existing buildings. It has been observed that energy performance improvement efforts are mostly directed towards the optimization of building design parameters in the design phase buildings.

3. Proposed Model

Inverse multiple criteria sorting problem is introduced into the literature by Mousseau et al. (2017). According to the proposed optimization models in that study, the aim of the problem is to determine the best actions for improving classes of predefined objects to desired classes or to obtain an improved classification for all of the objects subject to budget limitation.

Second model of Mousseau et al. (2017) is considered in this study. The proposed inverse multiple criteria sorting problem model with budget limitation aims to obtain the best sorting of objects subject to budget limitation. Decision variables are selection of possible actions and type of the variables are binary. Model parameters, decision variables and mathematical formulation of the model presented in this part as follows:

Parameters

q^{t-h} : coefficient for objects in class h

δ_{ijk} : effect of action k on object i in views of criteria j

O_{ij} : present condition of object i in views of criteria j

c_k : cost of action k

b_h : upper bound of weighted score for assigning an object to class h

B : budget limit

w_j : weight of criteria j

Decision variables

O'_{ij} : new condition of object i in views of criteria j

Y_{hi} : binary variable showing assignment status of object i to class h

X_k : binary variable showing selection of action k

Mathematical formulation:

$$\min \sum_{h=1}^{t} q^{t-h} \sum_{i=1}^{q} y_{hi} \qquad (1)$$

$s.t.$

$$o'_{ij} = o_{ij} + \sum_{k=1}^{m} \delta_{ijk} x_k \qquad , \forall i, j \qquad (2)$$

$$\sum_{k=1}^{m} c_k x_k \le B \qquad (3)$$

$$\sum_{h=1}^{t} y_{hi} = 1 \qquad , \forall i \qquad (4)$$

$$\sum_{j=1}^{n} o'_{ij} w_j \le b^{h+1} + M(1 - y_{hi}) \quad , \forall i, \ \forall h = 2, ..., t \qquad (5)$$

$$\sum_{j=1}^{n} o'_{ij} w_j \le b^{h} + M(1 - y_{hi}) \quad , \forall i, \ \forall h = 1, ..., t-1 \qquad (6)$$

$$x_k \in \{0,1\} \qquad , \forall k \qquad (7)$$

$$y_{hi} \in \{0,1\} \qquad , \forall h, i \qquad (8)$$

Objective function of the model is expressed in Equation (1). This equation ensures that the number of objects in undesired classes should be minimized. q^{t-h} values are determined smaller for the desired classes and greater for undesired classes. By this way, the number of objects in undesired classes are minimized.

Change of objects’ scores in views of criteria are expressed via the first constraint of the model. This constraint is given in Equation (2) and states that the change occurs only if the selected action causes a change for the object. Budget limitation is given with Equation (3) and total cost of selected action should not exceed the limit. Each object should be assigned to only one class. This restriction is expressed with Equation (4). The relationship between classes and weighted sum of object scores are expressed with Equation (5 – 6), where M is a great number. Sign restrictions of decision variables are given via Equation (7 – 8).

The given model is used in this study to improve energy efficiency of a site consisting 10 buildings by considering 7 sorting criteria. Data for the buildings, classification measures and alternative actions are explained in the fourth part.

4. An Example of Energy Efficiency Improvement

Applicability of the model is tested on an energy efficiency improvement in a building site example. This site is assumed to have 10 buildings and 7 criteria are considered to be effecting the energy efficiency in buildings. The sorting criteria are proposed by Kabak et al. (2014) and listed as follows:

- Location and climate data (C1)
- Geometrical shape (C2)
- Building envelope (C3)
- Mechanical Systems (C4)
- Lighting system (C5)
- Hot water system (C6)
- Renewable energy and Cogeneration (C7)

Let's assume that the buildings are assigned into 7 classes. Buildings are classified by comparing the weighted sum of scores on each criteria for each building with lower bound of efficiency classes. Kabak et al. (2014) calculate criteria weights via Analytic Network Process method. These weights are given in Table 1 as follows:

Criteria	C1	C2	C3	C4	C5	C6	C7
Weights	0.27	0.07	0.10	0.16	0.12	0.08	0.20

Tab. 1: Criteria weights

Upper bounds for classes for comparison with weighted sum of scores are presented in Table 2 as follows:

Class	A	B	C	D	E	F	G
Lower Bound	5	10	14	18	22	26	30

Tab. 2: Upper bounds of classes

Action	A1	A2	A3	A4	A5
B1	-8 for C2, -10 for C3	-9 for C4, -14 for C6	-5 for C5	-10 for C6	-8 for C7
B2	-7 for C2, -16 for C3	-15 for C4, -13 for C6	-16 for C5	-7 for C6	-9 for C7
B3	-15 for C2, -18 for C3	-18 for C4, -16 for C6	-10 for C5	-18 for C6	-22 for C7
B4	-11 for C2, -12 for C3	-7 for C4, -15 for C6	-7 for C5	-12 for C6	-10 for C7
B5	-18 for C2, -16 for C3	-19 for C4, -17 for C6	-16 for C5	-15 for C6	-25 for C7
B6	-19 for C2, -14 for C3	-6 for C4, -9 for C6	-4 for C5	-9 for C6	-7 for C7
B7	0 for C2, -2 for C3	0 for C4, 0 for C6	-1 for C5	0 for C6	-1 for C7
B8	-9 for C2, -17 for C3	-7 for C4, -12 for C6	-8 for C5	-9 for C6	-13 for C7
B9	-12 for C2, -6 for C3	-12 for C4, -15 for C6	-2 for C5	-14 for C6	-13 for C7
B10	-9 for C2, -9 for C3	-10 for C4, -8 for C6	-7 for C5	-8 for C6	-1 for C7

Tab. 3: Possible changes of building scores

The most desired class is A and G is the most undesired class. As it seen from Table 2, the aim of energy efficiency improvement problem is to minimize the value of weighted sum. Hence, the possible changes in building scores after energy efficiency improvement actions will be in negative numbers. There are five possible actions and these actions are determined as changing the roofs with most energy efficient roof type (A1), changing the HVAC system of buildings with the newest one (A2), changing the lighting systems with the most efficient one (A3), building a central hot water system (A4) and installing solar panels on roofs to support energy demand (A5). Possible changes in building scores (δ_{ijk}) are given in Table 3.

Cost of each action is determined as 300 Monetary Units (MU) for A1, 700 MU for A2, 100 MU for A3, 200 MU for A4 and 250 MU for A5, respectively. Building site management have allocated a budget of 750 MU for energy efficiency improvement actions and they are willing to determine the best improvement policy for overall energy efficiency. Scores are buildings are given in the scale of 0 – 30 for each criteria. Present scores of each building in views of each criteria are presented in Table 4:

Building	C1	C2	C3	C4	C5	C6	C7
B1	19	12	14	11	9	16	13
B2	23	15	23	20	19	15	18
B3	21	20	23	23	16	24	26
B4	14	19	16	9	8	18	15
B5	28	25	21	23	24	22	27
B6	22	26	28	8	7	13	12
B7	13	1	3	1	2	2	2
B8	20	13	22	10	10	15	15
B9	12	19	11	16	5	20	17
B10	12	16	15	11	7	9	3

Tab. 4: Present scores of buildings in views of each criteria

Initially these 10 buildings are assigned to classes D, E, F, C, F, D, A, D, C and B, respectively. Inverse multiple criteria sorting problem model is coded with GAMS optimization software to solve this energy efficiency improvement application on a personal computer with Intel Core i7 2.40 GHz processor and 8 GB RAM. Objective coefficient for classes are determined as 0, 10, 20, 30, 40, 50 and 60, from Class A to Class G respectively. Obtained results indicate that the objective function value is 160. The classes of buildings will be C, D, C, B, D, C, A, B, B and B, respectively after the suggested changes.

These results show that the best sort of buildings subject to a budget limit of 750 MU. Only classes of two buildings remains as the same of initial classes. The other buildings classes are improved. Furthermore, the classes of the emphasized buildings are A and B. They are already two of the most energy efficient buildings among the ten buildings. After the suggested changes, final scores of buildings are given in Table 5, as follows:

Building	C1	C2	C3	C4	C5	C6	C7
B1	19	4	4	11	4	16	5
B2	23	8	7	20	3	15	9
B3	21	5	5	23	6	24	4
B4	14	8	4	9	1	18	5
B5	28	7	5	23	8	22	2
B6	22	7	14	8	3	13	5
B7	13	1	1	1	1	2	1
B8	20	4	5	10	2	15	2
B9	12	7	5	16	3	20	4
B10	12	7	6	11	0	9	2

Tab. 5: Final scores of buildings

5. Conclusion

Due to the increasing attention on environmentally friendly approaches, energy efficiency becomes an important issue for building designers, construction companies and customers. Energy efficient buildings are taking attention of potential customers even more, because of the taxing, energy pricing and energy saving aspects of these properties.

Energy efficient buildings are also an interesting subject for researchers. In the last decade's literature there are different studies of this field. However, researchers generally focused on energy efficient design of new buildings. In this study, energy efficiency improvement of existing buildings problem is considered.

Inverse multiple criteria sorting problem is used to model the emphasized problem and an example of energy efficiency improvement is solved to demonstrate applicability of the model on this problem.

GAMS optimization software is used to solve the application of energy efficiency improvement of 10 existing buildings based on 7 criteria. Obtained results show that this model is a suitable solution method for energy efficiency improvement policy determination.

This study can be extended by considering different evaluation criteria for energy efficient buildings. Researchers may consider solving the problem by taking different constraints or objective functions into consideration. Another extension of the problem may be testing the solution capacity of integer programming solvers by solving examples of greater dimensions.

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