Advances in Energy and Materials Research https://jaem.qom.ac.ir/

Presenting and solving a bi-objective integer programming model to simultaneously optimize energy consumption and building construction costs by optimally selecting the type of materials and equipment required for building construction

H. Shirdel[1] **and Z. Alatwy**[2]

1. Corresponding author, Department of Mathematics, Faculty of Sciences, University of Qom, Qom, IRAN.
**Email of Corresponding Author: g.h.shirdel@qom.ac.ir*
2. Department of Mathematics and Computer Sciences, Faculty of Sciences, University of Qom, Qom, IRAN.

Article Info

Article type:
Research Article

Article history:
Received 28 Nov 2024
Received in revised form 23 Dec 2024
Accepted 12 Feb 2025
Published online 27 Mar 2025

Keywords:
Energy consumption, Optimization, Productivity, Integer programming.

ABSTRACT

Construction materials and equipment significantly influence both the initial building cost and its long-term energy performance. This study develops a bi-objective integer programming model aimed at simultaneously minimizing construction costs and operational energy consumption. The model selects the optimal combination of materials and equipment subject to structural and budgetary constraints. A linear programming formulation is proposed and solved using QSB++. The results demonstrate that integrating cost and energy considerations into a unified optimization framework can reduce total expenses while improving the building's energy efficiency. The proposed model provides a simple yet practical decision-support tool for designers and engineers.

Cite this article: H. Shirdel & Z. Alatwy, (2025). Presenting and solving a bi-objective integer programming model to simultaneously optimize energy consumption and building construction costs by optimally selecting the type of materials and equipment required for building construction, Advances in Energy and Materials Research, 2 (1), 11-18. https://doi.org/10.22091/jaem.2025.14494.1033

DOI: 10.22091/jaem.2025.14494.1033
Publisher: University of Qom.

1. Introduction

Housing is one of the fundamental needs of human society, and the construction industry has therefore become a vital sector that influences economic, social, and even political development. As urban populations grow and energy demands increase, the quality and type of construction materials used in buildings have become central considerations for engineers, policymakers, and developers. Advances in material science have led to the availability of diverse construction materials and equipment, each varying in cost, durability, and energy performance. Consequently, selecting the optimal combination of materials is no longer merely a technical choice but a strategic decision that affects both short-term construction expenses and long-term operational efficiency. Builders and planners consistently seek solutions that minimize total costs while maximizing building performance, particularly in terms of energy efficiency. Achieving such a balance is increasingly important as governments and housing authorities promote policies aimed at reducing environmental impact and improving the quality of residential infrastructure. These challenges highlight the growing necessity of applying optimization techniques to support rational decision-making in construction planning. Optimization provides a scientific framework for identifying the best set of materials and equipment under multiple, and sometimes conflicting, criteria. By integrating cost considerations with energy-performance metrics, optimization enables builders to select material combinations that deliver high productivity—defined here as the ability to reduce a building's operational energy consumption at the lowest feasible cost. In this study, we develop a linear programming model to assist in the optimal selection of construction materials and equipment. The model incorporates expert knowledge and field-based data to ensure practical relevance. An analytical method is used to solve the model and identify the optimal trade-off solutions. The results demonstrate that the proposed model can significantly minimize overall construction costs while simultaneously improving the energy efficiency of the building. An applied case study is also presented and solved using dedicated software, further validating the effectiveness of the proposed approach.

1. Research Background

The optimization of building construction—particularly with the dual objectives of minimizing costs and improving energy efficiency—has been an active research area for several decades. Numerous studies have investigated mathematical and computational approaches to support material selection, energy management, and sustainability in the built environment. This section provides a concise overview of significant contributions in this field. Castro Lacouture et al. developed an optimization framework based on a LEED-oriented scoring system to guide environmentally responsible material selection in building projects, demonstrating its application in Colombia [2]. Diakaki and colleagues proposed a multi-objective decision-making framework focused on enhancing the energy performance of buildings [3]. Kim et al. introduced a two-stage integer programming model for planning energy-efficient retrofits, implemented in South Korea [11]. Rahmani and co-authors presented a multi-objective optimization model aimed at improving energy efficiency in residential structures [14]. Zhang et al. proposed a multi-objective optimization model that reduces energy consumption using fewer control parameters compared to similar studies, employing a particle swarm optimization algorithm [17]. Shiripour and colleagues formulated a linear mathematical programming model designed to optimize energy usage in construction projects [15]. Ebrahimi Sarizadi et al. combined neural networks with a multi-objective genetic algorithm to evaluate building performance based on empirical construction data [5]. He and colleagues developed a bi-objective optimization model to balance investment costs and energy consumption in public buildings using the ε-constraint method [7]. Hosamo et al. integrated Building Information Modeling (BIM) with machine learning and NSGA-II to create a multi-objective framework that improves thermal comfort and energy efficiency [8]. Jalilibal and Bozorgi Amiri introduced a robust multi-objective optimization approach incorporating sustainability considerations for managing portfolios of construction projects [9]. Peng and co-authors conducted an influential study on integrated multi-objective optimization for prefabricated building systems using stability-level analysis [13]. Kabiri and Maftouni proposed a multi-objective optimization model targeting energy reductions in commercial buildings and emphasized the relevance of ecological materials, solving their model with genetic algorithms [10]. Etemad and Shafaat examined retrofitting strategies for cooling systems in historical buildings, offering practical insights into improving thermal performance in heritage structures [6]. Al-Kabaha et al. designed a multi-objective model that seeks to minimize construction costs and maximize energy efficiency gains in residential buildings while considering greenhouse gas emissions [1]. Dionyssis and colleagues studied energy and cost optimization in residential buildings, applying their multi-objective methodology to real cases in Patras, Greece [4]. Finally, Uthraa et al. introduced a predictive control approach for efficient energy and temperature management in buildings, demonstrating the practical role of Internet-of-Things technologies using embedded chips [16].

3. Problem Formulation

In this section, we present the notation, parameters, and decision variables used in the bi-objective optimization model. Table 1 summarizes the symbols and their corresponding descriptions.

Table 1. Description of Symbols

No.	Symbol	Description
1	I	Number of available raw material types.
2	k_i	Number of raw materials belonging to category i.
3	$\mathbb{Z}$	Set of integer numbers.
4	C_j^i	Cost of one unit of the j-th raw material in category i.
5	p_j^i	Productivity of one unit of the j-th raw material in category i.
6	U	Minimum required total productivity of the selected materials.
7	L	Set of available heating devices for the air conditioning systems.
8	U_i	Maximum allowable quantity of raw material type i.
9	L_i	Minimum allowable quantity of raw material type i.

Then, in Table 2, we present the decision variables used in the model.

Table 2: Components of Decision Variables

Number	Symbol of the Decision Variable	Description of the Decision Variable
1	$X_i^T = (x_i^1, x_i^2, \dots, x_i^{k_i})$	A vector specifying the number of raw materials of type $i$to be used in the construction of a building.

After defining the parameters and decision variables, we now specify the objective functions and constraints of the model. The **first objective function** aims to minimize the total construction cost and is expressed as:

$$Min\, F_1 = F(X_1, X_2, \dots, X_I) = \sum_{i=1}^{I} . \sum_{j=1}^{k_i} c_j^i x_j^i \qquad (1)$$

The objective function in (1) minimizes the total cost. The **second objective function** maximizes the total productivity (or energy efficiency contribution) of the selected materials and is written as:

$$Max\, F_2 = G(X_1, X_2, \dots, X_I) = \sum_{i=1}^{I} . \sum_{j=1}^{k_i} p_j^i x_j^i \qquad (2)$$

Objective function (2) therefore maximizes total productivity. Since the problem contains two conflicting objectives, a common technique for solving multi-objective optimization problems is to transform them into a single-objective model by applying a linear combination method. Accordingly, we set:

$$Min\{F_1 - F_2\} \qquad (3)$$

Then, we can rewrite the combined objective function as follows:

$$Min(F_1 - F_2) = Min \sum_{i=1}^{I} . \sum_{j=1}^{k_i} (c_j^i - p_j^i)\, x_j^i = Min \sum_{i=1}^{I} . \sum_{j=1}^{k_i} d_j^i x_j^i \qquad (4)$$

Where;

$$d_j^i = c_j^i - p_j^i \ \text{ for } \ i = 1,2, \dots, I \ \text{ and } \ j = 1,2, \dots, k_i. \qquad (5)$$

We now formulate the constraints of the optimization model as follows:

$$\sum_{i=1}^{I} . \sum_{j=1}^{k_i} c_j^i\, x_j^i \le U \qquad (6)$$

Constraint (6) ensures that the total cost does not exceed the specified upper budget limit.

$$\sum_{i=1}^{I} . \sum_{j=1}^{k_i} p_j^i\, x_j^i \ge L \qquad (7)$$

Constraint (7) guarantees that the total productivity does not fall below the required minimum level.

$$L_i \le \sum_{j=1}^{k_i} x_j^i \le U_i \ , \ i = 1,2, \dots, I \qquad (8)$$

Constraint (8) ensures that, for each material category i, the total quantity used does not fall below the specified lower bound and does not exceed the allowed upper bound. This constraint enables the decision maker to maintain an appropriate and balanced composition of raw materials in the construction process.

$$x_j^i \ge 0, \qquad i = 1,2, \dots, I, \ j = 1,2, \dots, k_i \qquad (9)$$

Constraint (9) guarantees the non-negativity and feasibility of all decision variables.

$$x_j^i \in \mathbb{Z}, \qquad i = 3,4, \dots, I, \ j = 1,2, \dots, k_i \qquad (10)$$

A subset of the raw materials must be selected in discrete quantities. Constraint (10) therefore ensures that the corresponding decision variables take integer values in the optimal solution.

4. Solving Method of the Designed Problem

The formulated problem is a constrained linear programming model with a single objective. However, since some of the decision variables are required to take integer values, the model becomes a mixed-integer programming problem. To obtain an optimal integer solution, the following procedure is applied.

4.1. Main Steps of the Method

Step One: We begin by relaxing the integer constraints and solving the resulting linear programming problem using the two-phase simplex method. If the relaxed problem is infeasible, the decision maker is advised to adjust the modifiable parameters to achieve feasibility. To minimize disruption to the original model, these adjustments are performed through a *minimum-change optimization* procedure. Once feasibility is restored, the relaxed problem is solved again using the two-phase simplex method to obtain an optimal basic feasible solution.

Step Two: After obtaining the optimal solution to the relaxed problem, we examine whether all variables that are required to be integers indeed satisfy their integrality conditions.

- If all such conditions are satisfied, the obtained solution is also the optimal integer solution, and the procedure terminates.
- If one or more integrality requirements are violated, we proceed to the next step.

Step Three: For each decision variable that violates the integer requirement, a cutting plane is constructed and added to the final simplex tableau to eliminate the fractional portion of the feasible region while retaining all legitimate integer solutions. Since the tableau remains optimal after the cut is added, we continue the process using the dual simplex method. At this point, one of the following outcomes occurs:

1. **An optimal integer solution is obtained**, meaning all integrality constraints are satisfied. In this case, the procedure is complete.
2. **No integer-feasible solution exists** under the current parameter settings. In such a case, the decision maker is advised to revise the adjustable parameters so that a feasible integer solution becomes attainable. As before, parameter modifications should be kept as small as possible, and the resulting adjusted problem is again solved through the above steps until an optimal integer solution is found.

4.2. Formulation of Cutting Planes

If we have the condition $x_j^i \in \mathbb{Z}$but the optimal answer does not give an integer value for x_j^{i*}, then we present the mathematical form of the cutting plane as follows. Since we used the two-phase simplex method to solve the problem, the optimal solution corresponds to the basic matrix. Therefore, each component of the solution can be written as a linear combination of the elements of the simplex tableau as follows:

$$x_j^{i*} = x_j^i + \sum_{P_k \notin B} x_{jk}^i P_k \qquad (11)$$

Here, x_j^{i*} is the component of the optimal solution, $x_{jk}^i$are the elements of the simplex tableau, and $B$is the basic matrix.

$B = [P_1\ P_2\ \dots\ P_r], r$ is the row rank of the constraint matrix.

Now we assume:

$$x_j^{i*} = \lfloor x_j^{i*} \rfloor + \theta_j^{i*}, 0 < \theta_j^{i*} < 1 \qquad (13)$$

With this assumption, the cutting plane is written as:

$$\psi_j^i - \sum_{x_{jk}^i > 0,\, P_k \notin B} x_{jk}^i x_j^i - \frac{\theta_j^{i*}}{\theta_j^{i*} - 1} \sum_{x_{jk}^i < 0,\, P_k \notin B} x_{jk}^i x_j^i = -\theta_j^{i*} \qquad (14)$$

5. Solving an Applied Problem: Case Study

In this section, we present present a real-world example of the proposed model, Where the case study considers the use of several batches of raw materials for constructing a building. The aim her, It is to select and use these materials in a way that minimizes total cost while maximizing the productivity of the materials in improving the building's energy performance. The problem involves eight batches of raw materials, and each batch includes the following ingredients. The eight batches of raw materials used in the case study are listed in Table 3. Each batch contains a specific group of materials, and the number of items included in each batch is shown in the last column. Table 3: Types of Building Materials.

Table 3: Types of building materials

Number of batches	Symbol of batch	Raw materials included in the batch	Number of batch members
1	A_1	Concrete block, Pumice block, Clay block, Solid plate, Perforated brick, Thermal insulation brick	|A1| = 6
2	A_2	Polystyrene block, Insulated block, Clay block, Glass wool block, Composite block, Thermal insulation deck	|A2| = 6
3	A_3	Single-pane window, Double-glazed window, Triple-pane window.	|A3| = 3
4	A_4	Compression chiller, Absorption chiller, Solar chiller	|A4| = 3
5	A_5	Hot-water boiler, Solar-powered hot-water boiler, Hot-water package, Solar hot-water package, Heat pump.	|A5| = 5
6	A_6	Solar greenhouse (north side of roof), Solar greenhouse (west side),	|A6| = 4

		Solar greenhouse (east side), Solar greenhouse (south side)	
7	A_7	Solar-powered air-conditioning chiller, Solar-powered hot-water boiler, Solar-powered cold-water package	|A7| = 3
8	A_8	Devices that generate heat using sunlight, Devices that generate cold using sunlight.	|A8| = 2

These batches represent the different categories of materials that may be selected for the construction project, and each batch includes several materials with similar functions or applications, and the decision model determines the appropriate quantities to be used from each group.

The cost values for each type of building material are presented in Table 4, and the productivity coefficients for the materials are shown in Table 5.

Table 4: Description of Costs

Number	Symbol	Description of the Symbol
1	c_j^1	Cost of one unit of type *j* building material used to build the walls
2	c_j^2	Cost of one unit of type *j* building materials used to build roofs
3	c_j^3	Cost of a type *j* window unit used in the building
4	c_j^4	Cost of a unit of type *j* cooling system used in the building
5	c_j^5	Cost of a unit of type *j* heating system used in the building
6	c_j^6	Cost of a unit of type *j* passive ventilation system used in building construction
7	c_j^7	Cost of a unit of type *j* active air conditioning system used in building construction
8	c_j^8	Cost of a unit of type *j* device that generates energy using sunlight

Table 5: Description of Productivity

Number	Symbol	Description of the Symbol
1	p_j^1	Energy productivity coefficient from using one unit of type *j* building materials for wall construction
2	p_j^2	Energy productivity coefficient from using one unit of type *j* building materials for roof construction
3	p_j^3	Energy productivity coefficient from using one unit of type *j*window in building construction
4	p_j^4	Energy productivity coefficient of a cooling system unit of type *j*
5	p_j^5	Energy productivity coefficient of a heating system unit of type *j*
6	p_j^6	Energy productivity coefficient of a passive air conditioning system unit of type *j*
7	p_j^7	Energy productivity coefficient of an active air conditioning system unit of type *j*
8	p_j^8	Energy productivity coefficient of a machine unit of type *j* that works using solar energy

Table 6: Decision Variables (Vector)

Number	Symbol	Description of the decision variable
1	X_1	A vector that determines the amount of each building material used in the construction of walls
2	X_2	A vector that determines the amount of each building material used in the construction of roofs
3	X_3	A vector that determines the number of each type of window used in the building
4	X_4	A vector that determines the number of each type of cooling system used in the building
5	X_5	A vector that determines the number of each type of heating system used in the building
6	X_6	A vector that determines the number of each type of passive ventilation system used in the building
7	X_7	A vector that determines the number of each type of active ventilation system used in the building
8	X_8	A vector that determines the number of each type of solar cell used in the building

The decision variables in this case study are vectors and are written as follows:

$$X_i^T = (x_1^i, x_2^i, \dots, x_{k_i}^i), \qquad i = 1,2,\dots,8$$

Where;

$$x_j^i, i = 1,2,\dots,8 \text{ and } j = 1,2,\dots,k_i$$

In Table 7, we describe the components of the decision variables as follows.

Table 7: Components of Decision Variables

Number	Symbol	Description of the decision variable
1	x_j^1	Amount of type *j* building materials that should be used to build the walls
2	x_j^2	Amount of type *j* building materials that should be used to build roofs
3	x_j^3	Number of types *j* windows that should be used in the building

4	x_j^4	Number of types j cooling systems that should be used in the building
5	x_j^5	Number of types j heating systems that should be used in the building
6	x_j^6	Number of passive types j air conditioning systems that should be used for the building
7	x_j^7	Number of active types j air conditioning systems that should be used for the building
8	x_j^8	Number of types j devices that generate energy using sunlight

Table 8: Values of I, L, and U

Number	Symbol	Amount
1	I	8
2	L	1450
3	U	1000000000

Table 9: Values of k_i, L_i, and U_i

Number	Symbol of vector	Symbols	Values
1	k_i	$k_1, k_2, k_3, k_4, k_5, k_6, k_7, k$	6, 6, 3, 3, 5, 4, 3, 2
2	L_i	$L_1, L_2, L_3, L_4, L_5, L_6, L_7, L$	76, 46, 66, 39, 38, 46, 76, 80
3	U_i	$U_1, U_2, U_3, U_4, U_5, U_6, U_7,$	325, 436, 845, 219, 768, 437, 856, 609

In Table 10, assuming $M_j^i = (c_j^i, p_j^i, d_j^i = c_j^i - p_j^i)$, we report the values of c_j^i, p_j^i, and d_j^i as follows.

Table 10: Values of c_j^i, p_j^i and d_j^i.

i	k_i	j	M_j^i
1	6	1	(2450, 0.68, 2449.32)
		2	(2135. 0.65, 2134.35)
		3	(4587, 0.71, 4586.29)
		4	(3347. 0.68, 3346.32)
		5	(6025, 0.90, 6024.1)
		6	(5480, 0.87, 5479.13)
2	6	1	(44320, 0.452, 44319.548)
		2	(57430, 0.512, 57429.488)
		3	(64560, 0.603, 64559.397)
		4	(75680, 0.784, 75679.216)
		5	(87320, 0.842, 87319.158)
		6	(96540, 0.933, 96539.067)
3	3	1	(24360. 0.671, 24359.329)
		2	(18960, 0.546, 18959.454)
		3	(14325, 0.356, 14324.644)
4	3	1	(123650, 0.937, 123649.063)
		2	(88720, 0.645, 88719.355)
		3	(45660, 0.45, 45659.55)
5	5	1	(75000, 0.684, 74999.316)
		2	(87900, 0.725, 878999.275)
		3	(124650, 0.85, 124649.15)
		4	(43670, 0.53, 43669.47)
		5	(34780, 0.45, 34779.55)
6	4	1	(1875, 0.535, 1874.465)
		2	(1650, 0.469, 1649.531)
		3	(1000, 0.453, 999.547)
		4	(1250, 0.485, 1249.515)
7	3	1	(65780, 0.86, 65779.14)
		2	(35470, 0.63, 35469.37)
		3	(44350, 0.70, 44349.3)
8	2	1	(542130, 0.98, 542129.02)
		2	(435690, 0.95, 435689.05)

With the above data, the mathematical model of the problem becomes as follows:

$$Min\ (\sum_{j=1}^{6} d_j^1\, x_j^1 + \sum_{j=1}^{6} d_j^2\, x_j^2 + \sum_{j=1}^{3} d_j^3\, x_j^3 + \sum_{j=1}^{3} d_j^4 x_j^4 + \sum_{j=1}^{5} d_j^5\, x_j^5 + \sum_{j=1}^{4} d_j^6\, x_j^6 + \sum_{j=1}^{3} d_j^7\, x_j^7 + \sum_{j=1}^{2} d_j^8\, x_j^8\ )$$

S. t.

$$\sum_{j=1}^{6} c_j^1\, x_j^1 + \sum_{j=1}^{6} c_j^2\, x_j^2 + \sum_{j=1}^{3} c_j^3\, x_j^3 + \sum_{j=1}^{3} c_j^4 x_j^4 + \sum_{j=1}^{5} c_j^5\, x_j^5 + \sum_{j=1}^{4} c_j^6\, x_j^6 + \sum_{j=1}^{3} c_j^7\, x_j^7 + \sum_{j=1}^{2} c_j^8\, x_j^8 \leq 1000000000$$

$$\sum_{j=1}^{6} p_j^1\, x_j^1 + \sum_{j=1}^{6} p_j^2\, x_j^2 + \sum_{j=1}^{3} p_j^3\, x_j^3 + \sum_{j=1}^{3} p_j^4 x_j^4 + \sum_{j=1}^{5} p_j^5\, x_j^5 + \sum_{j=1}^{4} p_j^6\, x_j^6 + \sum_{j=1}^{3} p_j^7\, x_j^7 + \sum_{j=1}^{2} p_j^8\, x_j^8 \geq 1450$$

$$\sum_{j=1}^{6} x_j^1 \leq 325$$

$$\sum_{j=1}^{6} x_j^2 \leq 436$$

$$\sum_{j=1}^{3} x_j^3 \leq 845$$

$$\sum_{j=1}^{3} x_j^4 \leq 219$$
$$\sum_{j=1}^{5} x_j^5 \leq 768$$
$$\sum_{j=1}^{4} x_j^6 \leq 437$$
$$\sum_{j=1}^{3} x_j^7 \leq 856$$
$$\sum_{j=1}^{2} x_j^8 \leq 609$$
$$\sum_{j=1}^{6} x_j^1 \geq 76$$
$$\sum_{j=1}^{6} x_j^2 \geq 46$$
$$\sum_{j=1}^{3} x_j^3 \geq 66$$
$$\sum_{j=1}^{3} x_j^4 \geq 39$$
$$\sum_{j=1}^{5} x_j^5 \geq 38$$
$$\sum_{j=1}^{4} x_j^6 \geq 46$$
$$\sum_{j=1}^{3} x_j^7 \geq 76$$
$$\sum_{j=1}^{2} x_j^8 \geq 80$$
$$x_j^i \geq 0 \ , \ i = 1,2,\dots,8 \ , \ j = 1,2,\dots,k_i$$
$$x_j^i \in \mathbb{Z} \ , \ i = 3,4,\dots,8 \ , \ j = 1,2,\dots,k_i$$

Using software QSB^{++}, we have solved the above problem and reported the optimal solution in Table 11.

Table 11: Values of optimum solution

i	k_i	j	x_j^i
1	6	1	45721.09
		2	2547.46
		3	34301.13
		4	21354.76
		5	936.04
		6	5478.23
2	6	1	3145.54
		2	22156.76
		3	2658.99
		4	4001.01
		5	21420.73
		6	11132.38
3	3	1	13
		2	8
		3	21
4	3	1	32
		2	20
		3	12
5	5	1	26
		2	7
		3	16
		4	11
		5	8
6	4	1	16
		2	10
		3	9
		4	27
7	3	1	11
		2	19
		3	4
8	2	1	32
		2	44

Conclusion and Future Works

In this study, the problems of minimizing construction costs and maximizing the energy efficiency of buildings were addressed through a dual-objective integer programming model. The bi-objective formulation was converted into a single-objective problem and solved using the simplex method. Cutting-plane techniques were then applied to restrict the feasible region so that the optimal integer solutions would lie at the corner points of the reduced polyhedron. The numerical results demonstrate that the proposed method successfully balances two conflicting objectives: reducing total construction costs while improving the building's energy performance. Although more energy-efficient materials might be available in practice, their higher prices may lead to suboptimal solutions, showing the importance of evaluating cost–benefit trade-offs carefully. Overall, the method proves effective from both operational and empirical perspectives, enabling building designers and contractors to input their specific project data and use the optimized outputs as a quantitative decision-making tool. The approach is also flexible enough to be adapted to other forms of the problem. Future work may proceed in several directions. First, one, two, or even all three components of the model—data, parameters, and decision variables—may be extended to incorporate imprecise, uncertain, interval-valued, random, or fuzzy representations, thereby enhancing the model's robustness. Second, as the problem size increases with a larger number of variables and constraints, new techniques will be needed to manage large-scale instances efficiently. Third, approximate solution methods may be developed for cases in which exact optimization becomes computationally prohibitive. Fourth, evolutionary approaches such as heuristic and meta-heuristic algorithms can be explored to obtain high-quality solutions for complex variants of the problem within reasonable computation times.

Conflict of Interests

The authors declare no conflicts of interests.

Acknowledgment:

The authors express their sincere appreciation to the editor and the reviewers for their valuable and

constructive comments, which have significantly improved the quality of this work.

Authors' Contributions

All aspects of this study were performed collaboratively by both authors. Both authors contributed equally and approved the final manuscript.

References

[1] Al-Kabaha, Y., Bataineh, K., & Aburabi, M. (2025). Multi-objective optimization of energy consumption, cost, and emission for a residential building. *Heliyon*, *11*(3), e42139. https://doi.org/10.1016/j.heliyon.2025.e42139

[2] Castro-Lacouture, D., Sefair, J. A., Florez, L., & Medaglia, A. L. (2009). Optimization model for the selection of materials using a LEED-based green building rating system in Colombia. *Building and Environment*, *44*(6), 1162–1170. https://doi.org/10.1016/j.buildenv.2008.08.009

[3] Diakaki, C., & Kampelis, N. (2010). A multi-objective decision model for the improvement of energy efficiency in buildings. *Energy*, *35*(12), 5483–5496. https://doi.org/10.1016/j.energy.2010.05.012

[4] Makris, D., Antzoulatou, A., Romaios, A., Malefaki, S., Paravantis, J. A., Giannadakis, A., & Mihalakakou, G. (2025). Optimizing energy and cost performance in residential buildings: A multi-objective approach applied to the city of Patras, Greece. *Energies*, *18*, 3361. https://doi.org/10.3390/en18133361

[5] Ebrahimi Saryazdi, S. M., Etemad, A., Shafaat, A., & Bahman, M. A. (2022). Data-driven performance analysis of a residential building applying artificial neural networks (ANN) and multi-objective genetic algorithm (GA). *Building and Environment*, *225*, 109633.

[6] Etemad, A., Zare, N., Shafaat, A., & Bahman, M. A. (2024). Assessing strategies for retrofitting cooling systems in historical buildings. *Energy Reports*, *11*, 1503–1516. https://doi.org/10.1016/j.egyr.2024.01.017

[7] He, L., & Zhang, L. (2022). A bi-objective optimization of energy consumption and investment cost for public building envelope design based on the ε-constraint method. *Energy and Buildings*, *266*, 112133. https://doi.org/10.1016/j.enbuild.2022.112133

[8] Hosamo, H., Tingstveit, M. S., Nielsen, H. K., Svennevig, P. R., & Svidt, K. (2022). Multiobjective optimization of building energy consumption and thermal comfort based on an integrated BIM framework with machine learning–NSGA-II. *Energy and Buildings*, *277*, 112479. https://doi.org/10.1016/j.enbuild.2022.112479

[9] Jalilibal, Z., & Bozorgi Amiri, A. (2022). A robust multi-objective optimization approach for construction project portfolio considering sustainability. *Journal of Industrial and Systems Engineering*, *14*(1), 163–186. https://www.jise.ir/article_137602_252164ad477f785663a5f3fd34252c03.pdf

[10] Kabiri, E., & Maftouni, N. (2024). Multiple objective energy optimization of a trade center building based on genetic algorithm using ecological materials. *Scientific Reports*, *14*, 9366. https://doi.org/10.1038/s41598-024-58515-8

[11] Kim, J., Son, D., & Jeong, B. (2017). Two-stage integer programming model for building retrofit planning for energy saving in South Korea. *Sustainability*, *9*, 2087. https://doi.org/10.3390/su9112087

[12] Majdfaghihi, M. H. (2023). *A multi-objective stochastic programming model for resilient and sustainable supply chains under uncertainty* (Doctoral dissertation). Western Michigan University. https://scholarworks.wmich.edu/dissertations/4036

[13] Peng, J., Feng, Y., Zhang, Q., & Liu, X. (2023). Multi-objective integrated optimization study of prefabricated building projects introducing sustainable levels. *Scientific Reports*, *13*, 2821. https://doi.org/10.1038/s41598-023-29881-6

[14] Rahmani, M., Shakouri Ganjavi, H., & Kazemi, A. (2017). Presenting a multi-objective optimization model to improve energy consumption efficiency of residential buildings. *Industrial Management Journal*, *9*(1), 103–128. https://doi.org/10.22059/imj.2017.214428.1007114

[15] Shiripour, S., & Mohammadnejad, M. (2021). A linear mathematical programming model for optimization of energy consumption in construction projects. *Journal of Energy Management and Technology*, *6*(2), 1–10. http://dx.doi.org/10.22109/jemt.2021.250917.1259

[16] Uthraa, K. R., Avraamidou, S., & Ganesh, H. S. (2025). Energy and temperature management in buildings through multi-objective model predictive control on a chip. *Computers & Chemical Engineering*, *192*, 108903. https://doi.org/10.1016/j.compchemeng.2024.108903

[17] Zhang, Y., Yuan, L., Zhang, Q., & Sun, X. (2020). Multi-objective optimization of building energy performance using a particle swarm optimizer with minimal control parameters. *Journal of Building Engineering*, *32*, 101505. https://doi.org/10.1016/j.jobe.2020.101505