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Integrated Design Optimization Process for Building Projects

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Abstract

In this study, a cost-design optimization is conducted for a reinforced concrete structure with irregular voids and inclined axes, which is a real-world application. Data transfers are performed on a 3D model to achieve the optimization. Data exchange is managed automatically by the created software program. As an application example, a hospital building with 10 beds is considered. Optimum design and minimum cost values are obtained for optimization processes using the Rao algorithms. The construction cost values are compared both among algorithms and with actual cost values, indicating a successful optimization process. The software program developed in this study accelerates the processes in optimization operations, thereby contributing to the realization of automatic data transfers.

Keywords

Rao algorithms, design optimization, gap irregularity, integrated software

1 Introduction

Although engineering solutions are known to follow a specific methodology, the results obtained are largely influenced by previous experiences and practical knowledge. In fact, the purpose is to perform the most reliable operation to meet the need, at the cheapest price. This involves searching for the best selection of solutions to optimize the problem.

The subject of design and cost optimization is frequently utilized in Civil Engineering, as in many engineering fields, and in all sub-disciplines. Its use can be classified as size, shape, topology, single or multi-objective optimization. It is possible to find a wide range of research studies related to the purposes of structures, material properties, and types of construction [1, 2]. Considering the material properties and system types, it can be seen that the amount of optimization on steel structures are relatively high [3, 4]. There are studies in which the size-shape optimization of planar and spatial lattice structures in steel structure systems [5], elastoplastic topology optimization of steel beams [6], optimization studies related to elastoplastic seismic analysis with material property changes [7] and the diagrid steel structure are optimized and the diagrid steel structure are optimized [8]. In steel structures, optimization is performed to reduce the total weight of the structures [9, 10]. When it comes to design-cost optimization problems and studies in reinforced concrete structures, researchers conducted in various forms, such as on the section, on the frame, and to a lesser extent in three dimensions. For instance, there are studies on the optimum design and cost optimization of rectangular reinforced concrete sections [11], studies that utilize artificial bee colony algorithms to optimize the total cost of reinforced concrete frames based on demand-to-capacity ratios of structural elements [12], and studies focusing on the optimum cost design optimization of various structural elements such as slabs, aiming to reduce the total cost including concrete and reinforcement steel [13, 14]. Studies exist on shape optimization of concrete arches with different forms of structural types [15], as well as studies on topology optimization of voids in external walls [16], various structural topology optimization studies [17, 18] and obtaining optimal values of technical analysis data for walls through efficient methods [19]. Bayrak et al. [20] performed the optimization of concrete pavements based on their mechanical properties. Tan et al. [21] designed the sewerage systems optimally with the differential evolution algorithm. Rausch et al. [22] performed topology optimization of architectural panels to minimize production

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consumption. Chutani and Singh [23] optimized the optimum design of reinforced concrete beams with particle swarm algorithm using Indian codes. Afzal et al. [24] discussed optimization studies in reinforced concrete structures and classified the applied methodologies as material efficiency, material-cost efficiency, environmental performance and sustainable design. Güvel and Karataş [25] optimized the construction rebar waste reduction using genetic algorithm. Giahchy et al. [26] applied cost optimization in the life-energy cycle for use in building projects. Sadat and Arslan [27] presented an optimization example for the prevention of torsional irregularity of a reinforced concrete framed structure. Esfandiary et al. [28] used particle swarm optimization and decision-making methods in reinforced concrete frames, with the objective function being cost of concrete, rebar and formwork. Salimi et al. [29] applied cascade optimization method for optimum design of reinforced concrete frames. Akin and Saka [30] optimized the fit search algorithm on reinforced concrete frame according to the provisions of ACI 318-05. Zakian and Kaveh [31] presented various information about seismic design optimization in structural engineering. Mangal and Cheng [32] presented a BIM-based framework for reinforced concrete structures, but the created system could only be applied to columns and beams in regular RC structure. Shoieb et al. [33] applied optimization by running the structural commercial programs SAP2000, ETABS, ROBOT, STAADPRO and RFEM together. Kazakis et al. [34] studied topology optimization for the need for computer-aided architecture. Aslay and Dede [35] performed the column, shear wall and beam removal scenarios using the SAP2000-OAPI feature. Akin and Saka [30] analyzed the design optimization of real-world reinforced concrete structures with a computing platform. Aslay and Dede [36] presented the optimization of a real-world reinforced concrete structure with MATLAB-ETABS-OAPI integration with Jaya algorithm. Kaveh and Rezazadeh Ardebili [37] Kaveh and Behnam [38], Kaveh and Sabzi [39] performed the optimization of 2D and 3D reinforced concrete frames using different metaheuristic algorithms.

Manual calculations of the design-cost optimization of reinforced concrete structures take a long time, leading to errors, over-design or incomplete designs due to the large number of calculations [40]. It is often observed that the cost estimated through optimization techniques exceeds the design code requirements or fails to meet the minimum design code requirements. Therefore, more work is needed on fully automating and optimizing reinforced concrete structures in 3D. At the same time, considering the entire frame structure, analysis of joint points, and optimizing reinforced concrete buildings with irregular structure is a deficiency that needs to be eliminated in the detailing of the optimization of steel reinforcements [24].

In this study, a software method is proposed for practical design and cost optimization of real-world reinforced concrete structures with gap irregularities and bent axes. The software program works like a computing platform and offers autonomous optimization processes. Integration is provided with the created software using the ETABS-OAPI feature. With the loop established in the MATLAB environment, the data is obtained repetitively, processed, and evaluated in the optimization flow. Rao algorithms were used as the optimization algorithm and shape optimization was reflected in the design. It has been tried to obtain the minimum value by iterating the most appropriate construction cost. The structures used in all these processes are not only reinforced concrete frames [41–43], but are also real examples with reinforced concrete frames and shear-walls. Structural analyzes were obtained as 3-dimensional and holistic. The obtained analysis data were taken directly with the integrated software and the previous best value was replaced with the new one by the optimization process. As a result, the design-cost optimization was successfully minimized.

2 Optimization algorithm

Rao algorithms are used in this study. These algorithms, also known as Rao series or Rao algorithms, seek solutions by focusing on developing simple optimization techniques that can provide effective solutions to complex problems. In any iteration i, where $f(x)$ represents the objective function to be minimized (or maximized), m design variables, and n candidate solutions (i.e., population size, $k = 1, 2, \ldots, n$) are assumed. For all candidate solutions, the best candidate is allowed to take the best $f(x)$ ($f(x)$best) and the worst candidate to take the worst $f(x)$ ($f(x)$worst) value. All candidate solutions i, k during iteration j for candidate the values of the variable are changed as in Eq. (1).

$$X'_{j,k,i} = X_{j,k,i} + r_{1,j,i}\left(X_{j,\text{best},i} - X_{j,\text{worst},i}\right) \tag{1}$$

$$\begin{aligned} X'_{j,k,i} &= X_{j,k,i} + r_{1,j,i}\left(X_{j,\text{best},i} - X_{j,\text{worst},i}\right) \\ &+ r_{2,j,i}\left(\left|X_{j,k,i} \text{ or } X_{j,l,i}\right| - \left|X_{j,l,i} \text{ or } X_{j,k,i}\right|\right) \end{aligned} \tag{2}$$

$$\begin{aligned} X'_{j,k,i} &= X_{j,k,i} + r_{1,j,i}\left(X_{j,\text{best},i} - \left|X_{j,\text{worst},i}\right|\right) \\ &+ r_{2,j,i}\left(\left|X_{j,k,i} \text{ or } X_{j,l,i}\right| - \left(X_{j,l,i} \text{ or } X_{j,k,i}\right)\right) \end{aligned} \tag{3}$$

In the above equations, $X_{j,\text{best},i}$ is the value of variable j for the best candidate, and $X_{j,\text{worst},i}$ is the value of variable j for the worst candidate during i^{th} iteration. $X'_{j,k,i}$ is the updated value of variable, and $r_{1,j,i}$–$r_{2,j,i}$ are two random numbers in the range [0, 1] for the j^{th} variable during the i^{th} iteration. In Eqs. (2) and (3), or $X_{j,k,i}$, $X_{j,l,i}$ terms indicate that the candidate solution k is compared with any randomly selected candidate solution l and information is transferred based on the fitness values. If the fitness value of the k^{th} solution is better than the fitness value of the l^{th} solution, then the term $X_{j,k,i}$ is used. If the fitness value of the i^{th} solution is better than the fitness value of the k^{th} solution, then the value of k is updated as $X_{j,l,i}$ instead of $X_{j,k,i}$ or $X_{j,l,i}$. Similarly, if the fitness value of the k^{th} solution is better than the fitness value of the i^{th} solution, then the value of i is updated as $X_{j,l,i}$ instead of $X_{j,k,i}$ or $X_{j,l,i}$. If the fitness value of the i^{th} solution is better than the fitness value of the k^{th} solution, then the term $X_{j,k,i}$ or $X_{j,l,i}$ is updated to $X_{j,k,i}$. This algorithm is based on the best and worst solutions in the population and random interactions between candidate solutions. This method does not require any algorithm-specific parameters and therefore eliminates the burden of the designer to adjust algorithm-specific parameters to obtain the best results.

3 Optimization parameter

3.1 Objective function

The objective function is provided in Eq. (4). In this equation, $f_{maliyet}$ is the approximate cost of the rough construction of the building, D_{bf} is the unit price of the Ministry of Environment, Urbanization, and Climate Change of the Republic of Türkiye (MoEU) rebar, D_m is the quantity of rebar. B_{bf} is the unit price of concrete belonging to MEUC, B_m is the quantity of concrete used in construction, K_{bf} is the unit price of formwork belonging to MEUC, and K_m is the quantity of formwork.

$$f_{maliyet} = D_{bf} \cdot D_m + B_{bf} \cdot B_m + K_{bf} \cdot K_m \,(€) \quad (4)$$

The penalized objective function is given in Eq. (5). C_K is the penalty coefficient. The objective function value $f_{(X)}$ is multiplied by the $(1 + C_K)$ value if the element does not comply with the constraints. The penalized objective function is represented by $Q_{(X)}$. The penalty value is obtained by multiplying the concrete quantity by a large number such as 10^9.

$$Q_{(X)} = f_{(X)} \cdot \left(1 + C_K\right) (€) \quad (5)$$

3.2 Design constraints

This study differs from other optimization studies due to the use of constraints and the function of constraints. As a reference, Turkish Seismic Code 2018 and TS 500 are used as constraints. However, the conditions in this regulation are not created as equations one by one. Instead, data is obtained from the package program as a result of the software cycle. In TS 500, structural safety calculations such as material coefficients, boundary condition conditions, bearing capacity calculations, load coefficients, load combinations, live load combinations, calculation openings, effective table widths, stiffness calculations, deflection control, and in TDBY 2018; earthquake ground motion spectrum calculations, design spectrum calculations, building usage classes, building importance coefficients, building height classes, building performance levels, limitation of relative floor displacements, second order effects calculations, modal calculation methods, ductility level calculations, cross section conditions. In this study, the constraints mentioned are not calculated manually, but automatically executed in the ETABS program.

3.3 Design variables

Design-cost optimization is applied to columns and beams within the scope of the study. The dimensions automatically obtained from the static program are provided in this section. As design variables, 225 different column cross-sections (300 mm × 300 mm – 500 mm × 1500 mm range) and 35 different beams (250 mm × 450 mm – 400 mm × 1000 mm range) sections are used. The design variable values are in the form of direct transfer of data in the static program using the computing platform created by the authors.

4 The 3D optimization of RC structures

Optimizing the design of real-world 3D RC building frame structures is very computationally difficult [39], and it is always expected to be supported by multiple software. In addition to the structural analysis program, it is necessary to use software that can effectively control this program. In this study, the authors use the structural analysis program ETABS [42] and MATLAB [43] software. In the Etabs program, unlike other structural software, certain source codes that enable the development of the program are shared for company owners and researchers. This feature is known as the Open Application Programming Interface (OAPI). This feature gives users the chance to manage the program with any software. In this research, optimization processes were automated by integrating the Etabs program using loops written in MATLAB. The process involves directing the structure using software to perform tasks such as initialization, analysis, section selection, design according to TBEC-2018, and continuously iterating the quantity data for optimization. Flowchart diagram and integrated software stages are given in Fig. 1. At the end of all stages, design-cost optimization processes for real-world 3D RC building frame structures have been carried out using Rao algorithms, regardless of whether the structure is element-based, single-frame, or reinforced concrete, and successful results have been obtained. The software has been designed to perform all operations, regardless of whether the structure is element-based, single-frame, or regular-irregular reinforced concrete. The software, developed and presented under the name ACDOS (Automated Cost Design Optimization of Structures), offers a practical solution by integrating the design-cost optimization of real-world reinforced concrete structures with autonomous processes. The proposed method offers advantages and innovations in the relevant field by being able to solve real-world concrete problems, obtain outputs according to market conditions, and not manually perform any of the analysis-data processing operations. The codes written in the MATLAB programming language assist in achieving the most optimal design results by enabling the integration of 3D reinforced concrete structures with ETABS-OAPI integration.

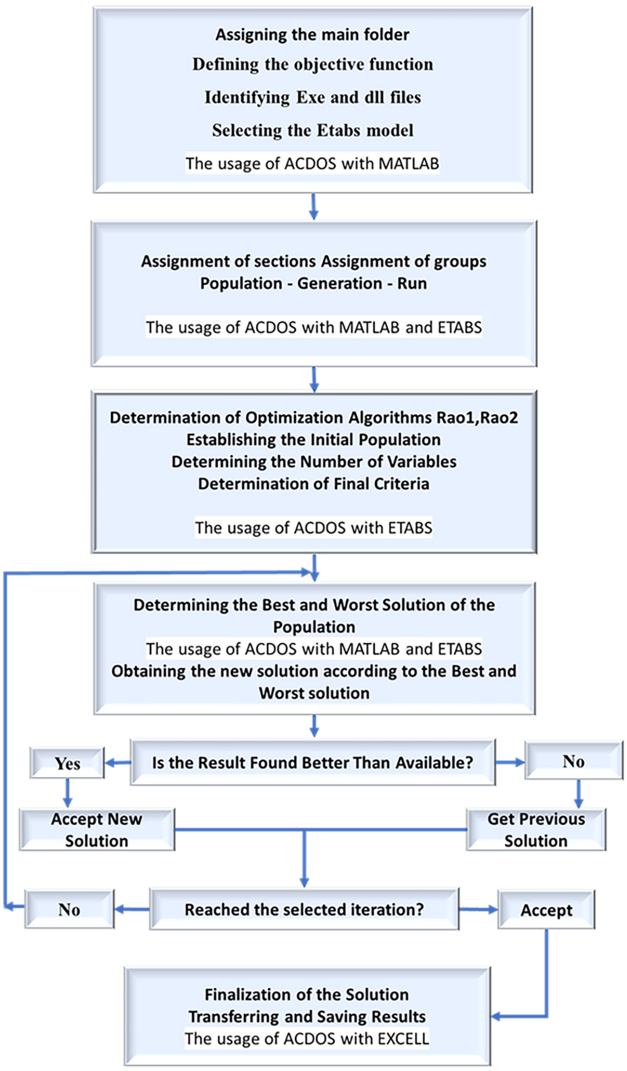


Fig. 1 Flowchart and the integrated software stages

5 Results

The static plan of the building used as a numerical example is given in Fig. 2. All columns and beams are divided into different groups. Building elements in similar locations are shown in the same color. For example, columns located on the outer axes in the *y-y* direction are shown in red, while columns located on the outer axes in the *x-x* direction are shown in blue. Internal columns are shown in pink, and middle columns are shown in green. Additionally, all exterior beams and interior beams are shown in orange. The optimization process is in the form of assigning the same cross-sections to elements of the same color. Thus, convenience is provided both in the field application and in the project phase. Cost-design optimization processes are successfully managed by making all groupings. All stages of optimization processes are presented in detail in other sections.

In this study, the numerical example is a public hospital building with 10 beds. The hospital has been especially chosen because it has structural irregularity and is classified as a building used immediately after the earthquake. The RC

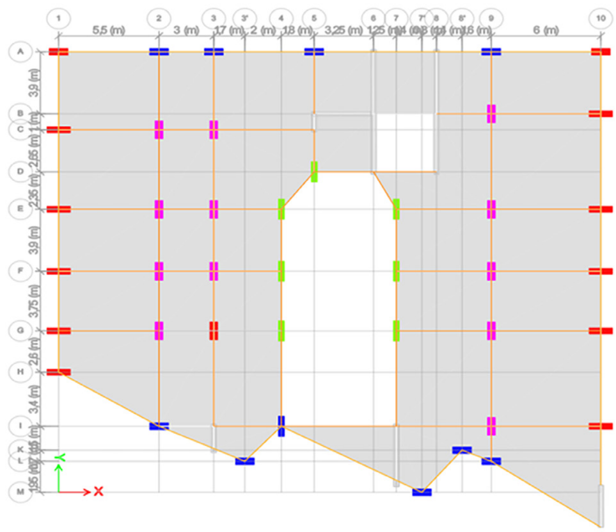


Fig. 2 Grouped RC structure static plan

building consists of a total of 3 floors, including basement + ground + 1 floor. The base floor area is 637 m^2 and the total construction area is 1913 m^2. The building has 126 columns, 32 curtains and 213 beams. There are RC shear-walls around the basement. It was built as a hospital. The year of construction is 2013. The image of the building is given in Fig. 3. Real-world RC structure is used in the study.

The total cost values for the hospital building, including concrete, steel, and formwork items, are evaluated under market conditions. The obtained values are determined under real construction-market conditions. The values for concrete, steel, and formwork are calculated considering both labor and material costs. Real quantity data is multiplied by the unit prices provided by the Ministry of Environment, Urbanization, and Climate Change to obtain the total approximate cost values. Two different algorithms are used for the design-cost optimization of the structure. These are Rao 1 and Rao 2 algorithms. At the same time, these algorithms are compared both among themselves and with the actual construction cost of the structure.

The objective function is the sum of the concrete, rebar and formwork costs of the reinforced concrete structure. The approximate cost value of the real-world reinforced concrete structure, obtained by multiplying the quantity values with unit prices, is given in Table 1. Turkish Building Earthquake Code 2018 [35] and Turkish Standards 500 [36] are used as the problem constraints. The ETABS program tests boundary conditions. Design variables include column cross-sections and beam cross-sections.

Fig. 3 The hospital building

Table 1 Approximate cost table

Items	Unit	Quantity	Unit price (€)	Amount (€)
Concrete	m^3	685.32	€ 49.14	€ 33,676.62
Steel	Ton	60.10	€ 942.94	€ 56,670.69
Formwork	m^2	4,713	€ 7.11	€ 33,509.43
Total cost				€ 123,856.74

Concrete cross-sections and rebar diameter-number are expressed as design elements. The reinforcement characteristics are established in accordance with the provisions of the regulations when there is a decrease or increase in the concrete cross-section. If the structural elements do not comply with the regulations, it is requested to re-select the element by creating a penalized objective function.

Table 1 presents the construction site data collected. According to Table 1, the concrete quantity is 685.32 m^3, steel is 60.10 tons, and the formwork covers an area of 4,713 m^2. The total approximate cost value calculated based on the site data is obtained as € 123,856.74. The model of the known building with the project information was created in the Etabs program. The program model was compared with the application model and the necessary controls were made for the static and architectural plans. In addition, grouping operations were carried out according to the position of columns and beam. The grouped 3D model of the building is given in Fig. 4. There are 5 different groups as columns $x1$-$x1$, $x2$-$x2$, $y1$-$y1$, $y2$-$y2$ and middle columns, and 2 different groups as inner and outer beams.

The model of the building prepared in the Etabs program is made ready to be optimized in the ACDOS program. Using Rao 1 and Rao 2 algorithms, 3D cost-design optimization is implemented in the building, which is a real-world structure. Each structural element is evaluated by considering different combinations of cross-section values used in practice. Quantity data obtained as a result of cost-design optimization with Rao 1 and Rao 2 algorithms are given in Table 2 and Table 3.

Rao algorithms are algorithms used in civil engineering problems and give consistent results. Rao 1 and Rao 2 algorithms are used in multivariate analyses and primarily

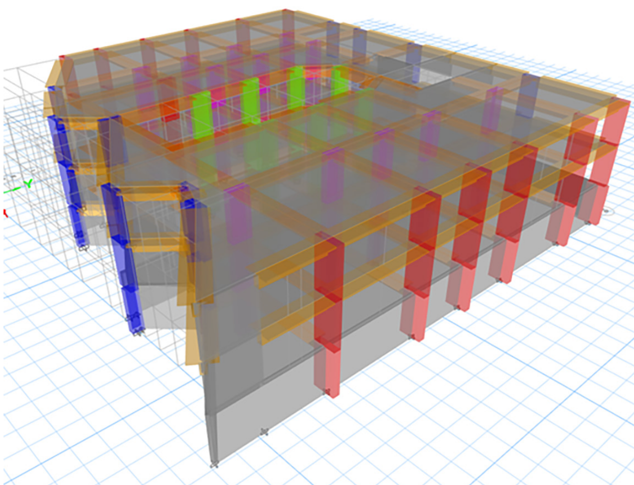


Fig. 4 Grouped 3D model

Table 2 Approximate cost table of Rao 1 algorithm

Items	Unit	Quantity	Unit price (€)	Amount (€)
Concrete	m^3	635.17	€ 49.14	€ 31,212.25
Steel	Ton	49.925	€ 942.94	€ 47,076.28
Formwork	m^2	4,368	€ 7.11	€ 31,056.48
Total cost				€109,345.01

Table 3 Approximate cost table of Rao 2 algorithm

Items	Unit	Quantity	Unit price (€)	Amount (€)
Concrete	m^3	646.82	€ 49.14	€ 31,784.73
Steel	Ton	49.22	€ 942.94	€ 46,411.51
Formwork	m^2	4,448	€ 7.11	€ 31,625.28
Total cost				€ 109,821.50

aim to find the most suitable parameter values in the dataset. The fundamental difference between these two algorithms lies in the strategy they employ when optimizing the problem. While Rao 1 utilizes the Fisher matrix, Rao 2 uses the Fisher matrix in a limited manner. Both algorithms conduct the optimization process by thoroughly evaluating the relationship between variables. The algorithms are being optimized with 30 populations, 100 iterations, and 10 runs. The column-beam sections, described in the previous sections in the floor plans, have 7 different groups. Columns are assigned to each outer axis, and middle columns in floor plans. Two different groups, external and internal, are assigned to the beams. The first section values of all groups, the final section values obtained with the Rao 1 algorithm and the last section values obtained with the Rao 2 algorithm are given in Table 4. Comparative initial and optimum cost data of Rao 1 and Rao 2 algorithms are presented in Table 5 (Concrete-formwork-rebar).

In the optimization process in the hospital building, 10 runs were applied. The analyzes reveal that the values of the run variable provide the best solutions for two algorithms, as depicted in Fig. 5. After reaching the minimum cost values of the algorithms, they continue at constant values until the 100th population. The Rao 1 algorithm achieves minimum results in approximately the 40th population and the Rao 2 algorithm in the approximately 10th population. However, the values obtained in both algorithms are very close to each other. While the cost is minimized to € 109,345.01 in the Rao 1 algorithm, the cost is minimized up to € 109,821.50 in Rao 2.

All 10 obtained running values are being compared (Fig. 6). As seen in Fig. 6, all operating values are completed at points close to each other. The algorithm application values of 10 runs, 30 populations, and 100 generations are found to be sufficient for the formation of the solution set. Solution values are given in comparison with both algorithms and actual construction costs. Although the Rao 1 and Rao 2 algorithms have similar values, the Rao 1 algorithm produces slightly better results with very small differences. The convergence graphs of the Rao 1 and Rao 2 optimization algorithms in the Hospital are given in Fig. 6.

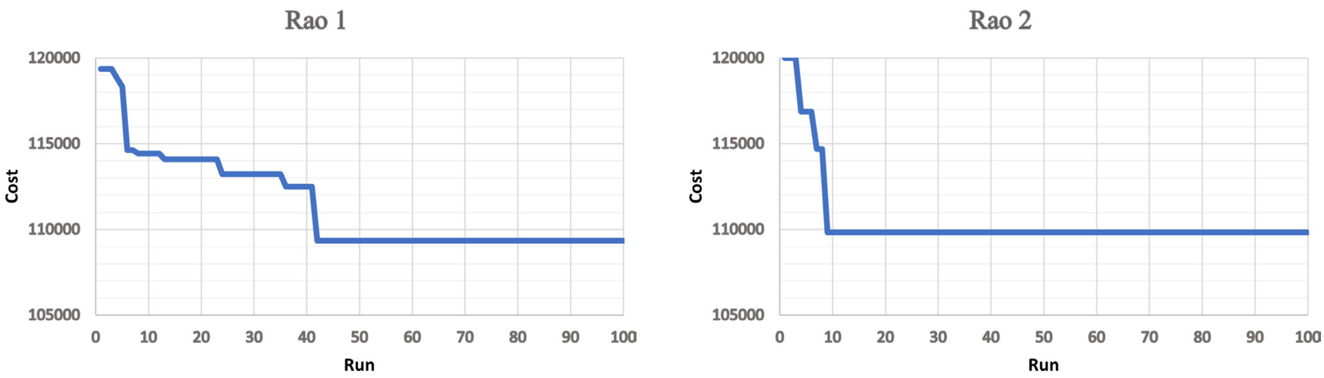
The cost values and reduction rates of the algorithms are given in Table 6. In the hospital building, Rao algorithms provide approximately 11% cost savings compared to the actual cost value. While the Rao 1 algorithm produces results parallel to the Rao 2 algorithm, it has been observed that the Rao 1 algorithm provides better results. Rao 1 has a minimum cost of € 109,345.01 and a reduction rate of 11.72%. Rao 2 has a minimum cost of € 109,345.01 and a reduction rate of 11.33%.

Table 4 Price analyses results

Algorithm	Run	Population	Generation	First cost	Optimum cost	Success rate
Rao 1	10	30	100	€ 123,856.74	€ 109,345.01	11.72%
Rao 2	10	30	100	€ 123,856.74	€ 109,821.50	11.33%

Table 5 Cross-sectional areas

Members group	First cross-section (m)	Optimum cross-section (m) Rao 1	Optimum cross-section (m) Rao 2
Perimeter columns 1	0.30 × 0.70	0.30 × 0.35	0.40 × 0.45
Perimeter columns 2	0.70 × 0.30	0.35 × 0.30	0.30 × 0.35
Perimeter columns 3	0.70 × 0.30	0.35 × 0.40	0.30 × 0.80
Perimeter columns 4	0.30 × 0.70	0.50 × 0.30	0.35 × 0.40
Middle columns	0.30 × 0.70	0.40 × 1.25	0.30 × 0.60
Exterior beams	0.30 × 0.60	0.50 × 0.30	0.40 × 0.50
Interior beams	0.30 × 0.60	0.35 × 0.40	0.25 × 0.65



(a) (b)

Fig. 5 Hospital building best solutions charts (Rao 1 and Rao 2)

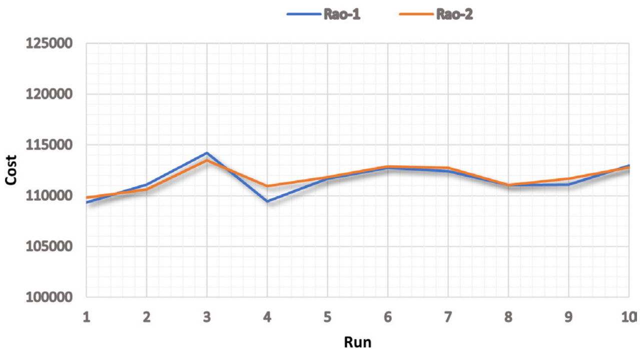


Fig. 6 Hospital building convergence graphs of Rao 1 and Rao 2 algorithms

Table 6 Hospital building comparison of cost reduction rates of different algorithms

Items	Site data	Rao 1	Rao 2
Building cost (€)	€ 123,856.74	€ 109,345.01	€ 109,821.50
Reduction percentage (%)	–	11.72%	11.33%

6 Conclusions

In this study, cost analyses were evaluated in the hospital building example by using Rao optimization algorithms. ACDOS computing platform has been suggested by the authors of the article for optimization processes. This platform performs automatic optimization of irregular real-world reinforced concrete structures under real loads. It uses ETABS-OAPI connection for data transfers. The study presents novelty in cost-design optimization by autonomously utilizing the ACDOS program to apply optimization methods in an irregular RC example.

The approximate cost of construction consists of concrete, formwork and rebar. Site data was requested from project engineers and control engineers. The authors of the article were also present at the construction site to conduct the necessary cost and cross-section inspections. Upon completion of the construction, the exact financial and concrete section values were obtained. According to the field data, the hospital building (concrete-rebar-formwork) used in the example cost € 123,856.74. With the ACDOS program, the structure has been optimized as it actually exists, with the Rao 1 and Rao 2 algorithms requested by the user. The optimization process was completed autonomously after some parameters determined by the user. As a result, the minimum cost value was reduced to € 109,345.01 with the Rao 1 algorithm, and the minimum cost value was reduced to € 109,821.50 with the Rao 2 algorithm. Concrete cross-section values obtained by both algorithms are also grouped and explained in detail in the text. As a result, in the optimization processes of reinforced concrete structures, a new generation example for autonomous cost-designs is presented to designer civil engineers in superstructure projects, both by using a real-world irregular structure and by performing automatic data management in the processes.

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