INTERNATIONAL JOURNAL OF OPTIMIZATION IN CIVIL ENGINEERING
Int. J. Optim. Civil Eng., 2020; 10(1):91-100

COST OPTIMIZATION OF RC FRAMES USING AUTOMATED MEMBER GROUPING

A. Kaveh[1*, †], R.A. Izadifard[2] and L. Mottaghi[2]
[1]*School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran*
[2]*Civil Engineering Department, Imam Khomeini International University, Qazvin, Iran*

ABSTRACT

In structural design, either the experience of designer is used or a uniform grouping is usually utilized to group the elements. This type of grouping affects the fundamental cost of the buildings, including the cost of concrete, steel and formwork, as well as secondary costs such as laboratory, checking, fabrication and etc. However, the secondary costs are not usually considered in the cost function. Strategies can also be used to automate the grouping of members in structural design. In this strategy beams and columns are automatically grouped into a limited number of groups to achieve the lowest cost. In this study, enhanced colliding bodies optimization algorithm is used to automatically group the beams and columns of the reinforced concrete structures and also to optimize their cost. The proposed procedure applied to three reinforced concrete frames with four, eight and twelve stories and the influence of automatic grouping of the members in optimal cost is investigated. Using this method, the beams and columns are automatically grouped and the results show that the optimal cost obtained from the automatic grouping is less than the manual grouping of the members.

Keywords: optimal cost; reinforced concrete frames; automatic grouping; enhanced colliding bodies optimization (ECBO).

Received: 10 August 2019; Accepted: 5 December 2019

1. INTRODUCTION

In structural design, designers usually avoid varying the dimension of structural members and try to group them. Increasing the number of groups has significant effects on the cost of construction such as laboratory, checking, fabrication, welding, and so on, but these costs

[*]Corresponding author: School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran
[†]E-mail address: alikaveh@iust.ac.ir (A. Kaveh)

are not included in cost function. On the other hand, the process of grouping the elements affects the cost of the building such as the cost of concrete, steel, and so on. The effectiveness of the manual grouping depends on the skill of the designer to identify the members of each group. In many optimization studies [1-3], the object is to reduce the cost of material including the amount of concrete and steel and formwork. The higher the number of groups for members leads to lower cost, but increases the cost of fabrication, welding, laboratory, checking, etc. Therefore, by using automatic grouping procedure that is known cardinality constraints, the optimization algorithm enables to groups the beam and column elements into a limited number. Limited number of studies have been conducted on the optimization of structures by considering automatic grouping. Barbosa et al. [4, 5] used a genetic algorithm encoding for automatic grouping of truss bars. Lemonge et al. [6] employed a special genetic algorithm encoding to minimize the weight of steel frames and automatic grouping of beams and columns. In which the frames were subjected to gravitational and lateral loading. Angelo et al. [7] utilized the ant colony optimization algorithms to solve the multi-objective optimization truss structures where they used cardinality constraint in the problems. Carvalho et al. [8] used the Craziness based Particle Swarm Optimization to optimize the size and shape of truss structures to minimize the weight of the structure. They used automatic grouping process to group the bars of the trusses. Kripka et al. [9] have used a software program, which combins a structural analysis of the floor of a building using a grid model and simulated annealing method, to minimize the cost of the beams in the RC buildings. They used the automatic grouping method to group the beams, in which only the height of the beam was considered as a variable. In another study, Boscardin et al. [10] employed the Harmony Search to optimize the cost of the RC buildings, where only the columns were grouped automatically.

There are fewer studies on the automatic grouping of the members of RC buildings. In the past studies, automatic grouping of columns [10] and beams [9] have been discussed separately. In this study, the enhanced version of the Colliding Bodies Optimization (CBO) algorithm [11] so-called ECBO [12] is used to optimize the cost and automatic grouping of the beams and columns of the RC frames. Here, the depth and width of cross sections, the number and diameter of bars in beams and columns are considered as the variables of the optimization. Furthermore, the number of groups for beams and columns considered as variable, where the members are grouped together is automatic manner. The design constraints are based on the ACI 318-08 [13] code.

After this introduction, a brief explanation of the algorithms used in this paper is presented in Section 2. In the Section 3 the formulation of optimization problem described. In Section 4, the proposed procedure for optimization in three frames is discussed. Finally, conclusions are presented in Section 5.

2. ENHANCED COLLIDING BODIES OPTIMIZATION

The Colliding Bodies Optimization (ECBO) algorithm was proposed by Kaveh and Mahdavi [11]. The basic idea of this algorithm is inspired by the theory of moving objects, where the moment before the collision is equal to the sum of the moment after the collision. To obtain reliable solutions and fast convergence, Kaveh and Ilchi Ghazaan [12] has been developed the enhanced colliding bodies optimization algorithm. In this algorithm, the solutions obtained at each step are modified by applying Colliding Memory (CM). ECBO stores some of the best Colliding Bodies (CBs) found in the previous population in each iteration and replaces them with the worst CBs in the current population. To improve the exploration capabilities and prevent premature convergence, one component of CBs is randomly regenerated any iteration. This parameter that is called as *pro* is within (0, 1). Detailed concepts and many applications of CBO and ECBO can be found in Refs. [14, 15, 16].

2.1 The procedure used in ECBO algorithm for automatic grouping

In this study. the ECBO algorithm is used for automatic grouping of beams and columns. The definition of variables for automatic grouping of members is based on the special encoding of the genetic algorithm [5]. First, databases containing design variables are created for beams and columns, and then the number of groups for the beams and columns are specified. Suppose 3 groups to be considered for beams and 3 groups for columns and the frame has 8 beams and 16 columns.

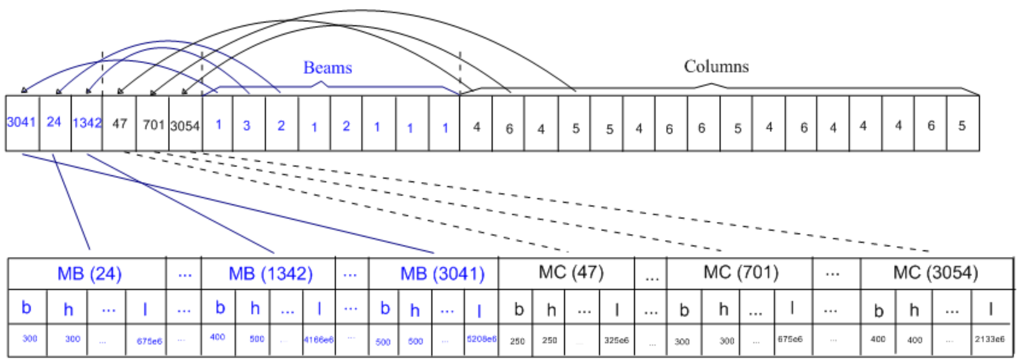


Figure 1. the procedures of automatic grouping in ECBO algorithm

According to Fig. 1 a number is randomly selected for beam members between 1 and 3, and for column members, a number between 4 and 6 is randomly selected. For the left bits (beam and column groups), a number is randomly selected from the databases. For beams (MB) between 1 and 34976 and for columns (MC) between 1 and 3060. For example, if we determine the moment of inertia for the beams in third story, we have:

$$I = MB(x(x(9)), 11)$$

where *I* represent the moment of inertia for the cross-section and *MB* is the database of beams. $x(9)$ represents the random number of bits 9, which is a number between 1 and 3 (group number). If $x(9)$ =2, means this beam is in the second group. Then the random number of the second bit is recorded, which represents a cross section of the beam database. If $x(x(9))$ = 24, it means that the twenty-fourth section from the beams database are selected. I= *MB* (x (x (9)), 11) means the row 24 and column 11 of the beam database, indicating the moment of inertia for the cross section. This process automatically determines the problem variables and the grouping of the beams and columns in a limited number to achieve the minimum cost.

3. FORMULATION OF OPTIMAL DESIGN

3.1 Design variables

Design variables of the optimization are as follows:

The geometry of the cross-section of columns (depth and width), the geometry of the cross-section of beams (depth and width), diameter and number of longitudinal bars in beam sections, diameter and number of longitudinal bars in the column sections. The variables defined in the form of discrete variables. For automatic grouping, the number of groups for beams and columns in the limited number are considered as variables.

3.1.1 Formation of Structural Element Databases

Most of the formulations of this section are adopted from [17].

Formation of database for beams: For each beam section the database includes the width and depth of the sections, the diameter and number of longitudinal bars (in the compression and tension zone), moment of inertia, bending capacity, and the cost per unit length of the beam. The sections of beams are considered as rectangular with the depth-to-width ratio of 1:2.5. Bounds of variables are provided for each example in the next section. At the final step, the bending capacities of the sections are calculated, and the database are stored in an ascending order based on increasing bending capacity.

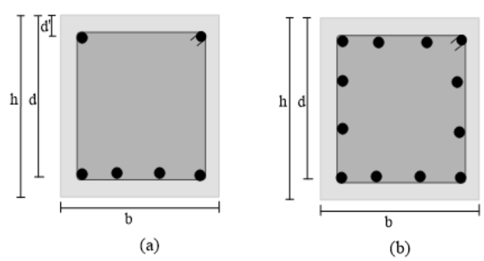


Figure 2. Cross-section of the beams and columns

The bending moment capacity of RC beams is defined as:

$$M_n = A_s f_y \left(d - \frac{a}{2}\right) \tag{1}$$

where A_s is the total area of tensile reinforcing bars, f_y is the yield strength of the bars, d is the distance from the edge of the section to the centroid of tension reinforcing bars (Fig. 2), and a is the depth of the equivalent rectangular stress block defined as:

$$a = \frac{A_s f_y}{0.85 f_c' b} \tag{2}$$

Here, f_c' is the compressive strength of the concrete and b is the width of the section. The database for beams is defined in Table 1. Limitations in the database that do not require structural analysis as a percentage of permissible bars, the distance of bars, and depth-to-width ratio are controlled. The sections which do not meet these limitations are removed from the database.

Table 1: Database of the beams [17]

Beam number	**Width (mm)**	**Depth (mm)**	**Number of bars**		**Dimeter of bars (mm)**		**Factored moment resistance (N.mm)**		**Moment of inertia (10^6 mm^2)**
			Compressive	Tension	Compressive	Tension	Compressive	Tension	
1	150	190	1	2	12.7	9.525	8192215	9274052	30
2	170	190	1	2	12.7	9.525	8238487	9332614	34
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Formation of database for columns: The data for a column in the database include the width and depth of sections, the diameter and the number of the longitudinal bars, moment of inertia, and the cost per unit length of the column. The parameters related to the P-M interaction diagram are calculated according to the ACI code and saved in the database in order to calculate the capacity constraints. The bounds of the variables are given for each example in the next section. In final step, the area for the P-M interaction diagram of the sections is calculated, and the sections are stored in ascending order.

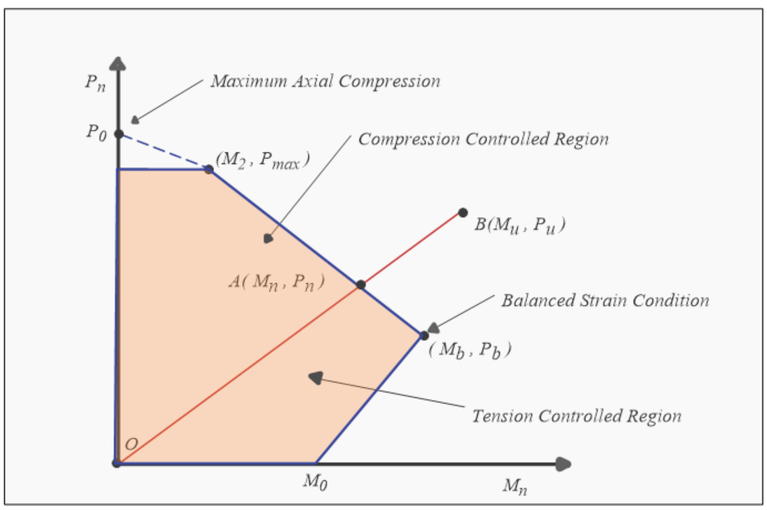


Figure 3. Load-moment interaction diagram for columns [17]

The database for the columns is provided in Table 2. In this database as well as the database of beams, the limitations that do not require structural analysis as a percentage of permissible bars, distance of bars are controlled. The sections that do not fulfill these limitations are deleted from the database.

Table 2: Database for the columns [17]

Column number	**Width (mm)**	**Depth (mm)**	**Dimeter of bars**	**Number of bars**			$\mathbf{P_{max}}$ **(N)**	$\mathbf{P_b}$ **(N)**	$\mathbf{M_b}$ **(N.mm)**	$\mathbf{M_2}$ **(N.mm)**	$\mathbf{M_0}$ **(N.mm)**
				Top	Inter	Bot					
1	250	250	9.525	4	2	4	1.27e6	0.44e6	52.7e6	14.65e6	31.77e6
2	250	250	12.7	3	0	3	1.28e6	0.43e6	52.9e6	14.52e6	33.37e6
⋮	⋮	⋮		⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

3.2 Objective function

The objective function of this study is to optimize the cost of building materials. The general form of the objective function is as follows:

$$f_k = \sum_{i=1}^{n_b+n_c} \{C_c b_i h_i + C_s A_{si}\} L_i + \sum_{i=1}^{n_b} \{C_f\big(b_i + 2(h_i - t_i)\big) + C_t b_i\} L_i + \sum_{i=1}^{n_c} \{2C_f(b_i + h_i)\} L_i \tag{3}$$

where n_b and n_c are the number of beams and columns, respectively; b_i, h_i, A_{si} and L_i are the width, height of the sections, area of the bars and the length of members, respectively; t_i is the thickness of the slab that is considered to be 290 mm; and C_c , C_s , C_f and C_t are the unit rate of concrete, bars, formwork, and scaffolding, respectively. Their values for the objective function are given in Table 3 (adopted from Ref. [18] [19]).

Table 3: Unit prices adopted from [18]

Description	Cost (€)	
	Beam	Column
Steel B-500 (kg)	1.3	1.3
Concrete HA-25 (m^3)	78.4	77.8
Concrete HA-30 (m^3)	82.79	82.34
Formwork (m^2)	25.05	22.75
Scaffolding (m^2)	38.89	-

3.3 Design constraints

Design variables must satisfy the limitations and specifications provided by the utilized codes. One method is the use of the penalty function. Here, the constrained problem is transformed into an unconstrained problem, and the design variables with penalty are removed in the following iterations.

$$f_p(x) = f \times (1 + \sum_{i=1}^{n} \max(0, g_i(x)))^{\,k} \tag{4}$$

where f_p represents the penalized objective function, f denotes the value of the objective function, x indicates the elements, g_i shows the penalty of the i th constraint, n is the number of constraints, and k denotes a penalty exponent. In this study k is considered as 2.

3.3.1 Constraint of beams

In this study, the RC beams are designed to resist the applied bending moments. The penalty function for the moment capacity of the beams is expressed as Eq. (5), and the constraints are controlled for the positive bending moments and the negative bending moments of the beam sections.

$$g_1 = \frac{|M_u| - \emptyset M_n}{\emptyset M_n} \tag{5}$$

where M_u is the applied ultimate bending moment, $\emptyset$ is the strength reduction factor which is equal to 0.9 for tension-controlled section and 0.65 for compression-controlled section, in the sections between tension and compression the magnitude of $\emptyset$ is calculated by a linear relationship between net tensile strains of 0.002 and 0.005. M_n is the nominal bending moment capacity of the RC beams.

The constraint of the minimum reinforcement section of beams is as:

$$\rho_{min} = \frac{\sqrt{f_c'}}{4f_y} \geq \frac{1.4}{f_y} \qquad g_2 = \rho_{min} - \rho \tag{6}$$

The constraint of the maximum reinforcement section of beams is:

$$\rho_{max} = 0.85\, \beta_1 \frac{f_c'}{f_y} \frac{600}{600+f_y} \qquad g_3 = \rho - \rho_{max} \tag{7}$$

Bending concrete members such as beams have bending deformation under applied load. Such a deformation, so-called deflection, should be controlled. In this study, a penalty is considered as the following for controlling the deflection of the beams:

$$h_{min} = \frac{L}{21} \quad g_4 = \frac{h_{min} - h}{h_{min}} \tag{8}$$

In order to prevent fracture failure in the section of the beams, the height of the compressive stress block should not be greater than the effective depth of the beam.

$$g_5 = \frac{a - d}{d} \tag{9}$$

The penalty of the minimum distance between bars is:

$$s_{min} = \max\,(d_b, 1\ inch) \quad g_6 = \frac{s_{min} - s}{s_{min}} \tag{10}$$

Since the bending moment capacity of the beam sections in the negative and positive zones are evaluated separately, the reinforcement topology constraints should be controlled at the top and bottom of the sections.

3.3.2 Constraint of columns

The cross-section of a column is suitable when the combination of (M_u, P_u) under the applied loads falls inside the interaction P-M diagram. The penalty function for the capacity of the column can be expressed as:

$$g_7 = \frac{l}{l_0} - 1 \tag{11}$$

Based on Fig. 3, in Eq. (11), l is the distance between the origin of the interaction diagram (O) and the point indicating the position of combination (M_u, P_u) (B), and l_0 is the radial distance between the origin of the interaction diagram (O) and the point (A) indicating the intersection point of the vector l with the interaction curve.

According to the ACI code, the total area of reinforcing bars (A_s) in the compression member has to be more than 1% and less than 8% of the gross section area (A_g). The penalty function for limitation of minimum longitudinal reinforcement for the columns is expressed as:

$$g_8 = \frac{0.01 \times A_g}{A_s} - 1 \leq 0 \tag{12}$$

And the penalty for maximum longitudinal reinforcement is expressed as:

$$g_9 = \frac{A_s}{0.08 \times A_g} - 1 \leq 0 \tag{13}$$

The penalty function for the limitation of clear distance between longitudinal bars is defined as:

$$s_{min} = \max\,(1.5 d_b, 1.5\ inch) \quad g_{10} = \frac{s_{min} - s}{s_{min}} \tag{14}$$

The dimensions of columns in each story should be smaller or equal than the dimensions of columns in its bottom story, so the constraints are expressed as follow:

$$g_{11} = \frac{b_T}{b_B} - 1 \tag{15}$$

$$g_{12} = \frac{h_T}{h_B} - 1 \tag{16}$$

$$g_{13} = \frac{n_T}{n_B} - 1 \tag{17}$$

where B and T represent the bottom column and the top column, b and h are the width and depth of the column cross section respectively, n is number of bars.

4. NUMERICAL EXAMPLES

Three examples are considered to investigate the proposed procedure for automatic grouping and its effect on optimal cost. These examples have already been optimized by Kaveh et al. [17], in which the grouping of members has been performed manually before the optimal design. Other exaamples of RC frame can be found in Refs. [20, 21]. In this study, the cost of all three frames are optimized once with using automatic grouping procedure for beams and columns and also with manual grouping, and the results are compared. It should be noted that in the manual grouping of this study, group members are assumed to be uniform in the storys. It is also assumed that the dimensions of columns in each story should be smaller or equal than the dimensions of columns in lower story, so the constraints Eqs. (15 to 17) have been added to solve these examples. In addition, the compressive strength of the concrete is considered in the first example as 30 MPa. In order to determine the demand of elements, the equivalent static analysis is performed via Opensees (2012) software [22] and the limitations of the ACI code are handled in MATLAB software [23]. The link of Opensees and MATLAB software is utilized for the optimization process. In the moment of inertia for the cross sections the effects of cracking have been taken into account according to the ACI code. To avoid duplication, one can refer to [17] for details of loading, variables ranges and materials specifications.

4.1 Example 1: A two-bay and four-story frame

The first example is a two-bay and four-story frame. Fig. 4 shows the geometry and numbering of the beams and columns. Here, the height of each story is 3 meters, the length of each bay is 5 meters. The distance between the parallel frames is 5 meters and the slab thickness for floors is 290 mm.

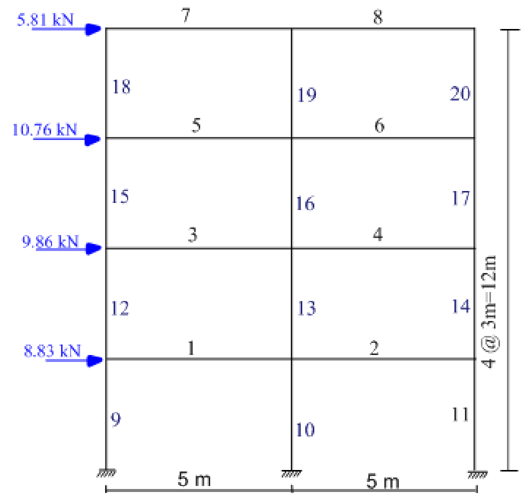


Figure 4. The geometry of the 2-bay and four-story frame

According to Fig. 4, the link of the members in the groups is shown in Table 4, in which the beams of each story and the side columns of each story in the frame are in the same group.

Table 4: Member grouping for the 2-bay and 4-story frame

Group	Members	Group	Members	Group	Members
B1	1,2	C5	9,11	C9	10
B2	3,4	C6	12,14	C10	13
B3	5,6	C7	15,17	C11	16
B4	7,8	C8	18,20	C12	19

The results of optimal cost for the 4-story frame with automatic grouping and manual grouping are presented in Table 5. In this table the nodcs represent the number of distinct cross sections, mg is the upper limit for the number of groups for beams and mc is the upper limit for the number of groups for columns. For the algorithm, the CM is assumed to be half the population size and the stopping criterion for terminating the algorithm is 2500 iterations. The values of other parameters (*pop* (population) and *pro*) for the algorithm are given in Table 5. The results show that by applying the automatic grouping procedure for beams and columns, the optimal cost has been decreased. Fewer distinct sections are also used, this resulted in reduction of the costs of fabricate, laboratory, checking, etc., which are not included in the cost function. Here the number of groups for beams and columns is limited to four, although the number of distinct sections used for automatic grouping method is less than manual grouping method, the optimal cost has been reduced by 4.3%. In Fig. 5 the optimization results for automatic and manual grouping methods are compared. Table 6 and Fig. 6 present the results of optimization and the allocation of beams and columns for groups based on the automatic grouping method.

Table 5: Summary of the optimization result for the 2-bay 4-story frame with and without automatic grouping procedure

Grouping procedure	**Upper limit of groups**	**Cost (€)**	**ndcs**	**The parameter of algorithm**	
				pro	pop
Automatic grouping	mg=mc=2	3328.4	4	24	0.7
	mg=mc=4	3220.84	5	22	0.7
Manual grouping	mg=mc=2	3376.92	4	22	0.75
	mg=mc=4	3358.29	7	22	0.45

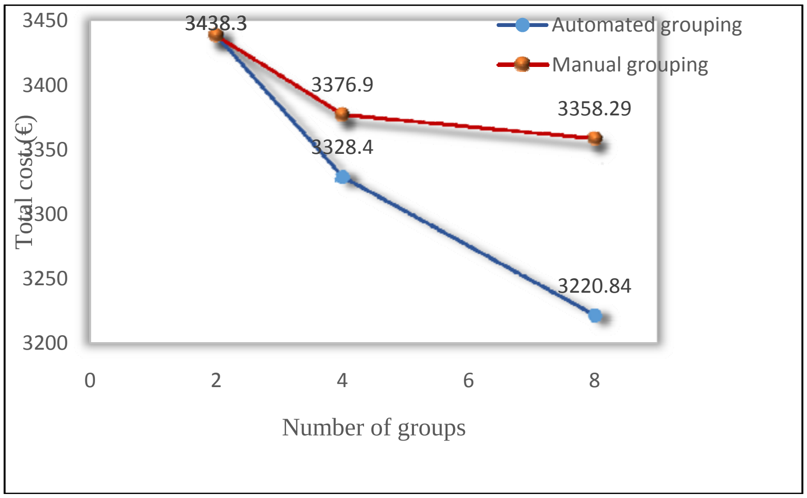
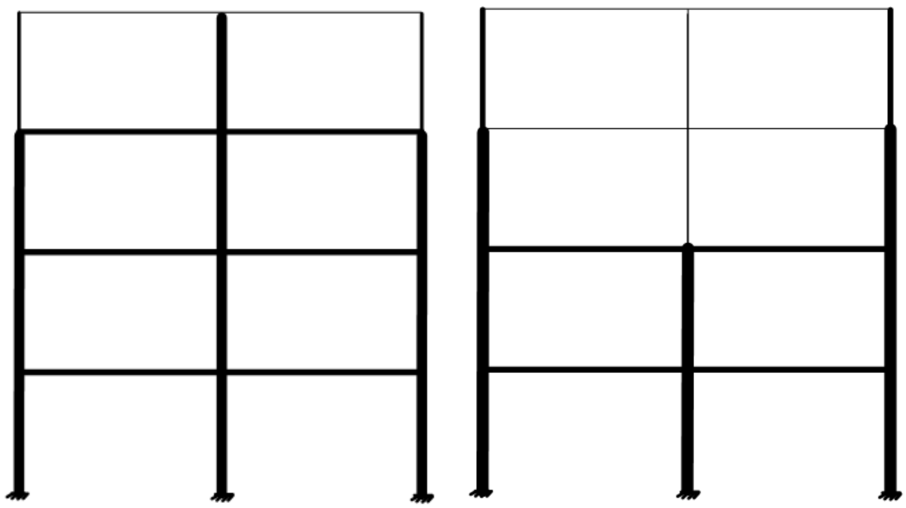


Figure 5. Comparison of the results of the optimization for the 2-bay and 4-story frame with and without automatic grouping

Table 6: Assigning the members to groups by using automatic grouping for 2-bay and 4-story frame

	Group	**mg=2 mc=2**				**mg=4 mc=4**			
		b (mm)	**h (mm)**	**A_s top**	**A_s bottom**	**b (mm)**	**h (mm)**	**A_s top**	**A_s bottom**
Beam	B1	190	430	2#8	1#8	190	430	1#11	1#8
	B2	190	430	2#8	1#8	190	430	1#11	1#8
	B3	190	430	2#8	1#8	190	410	1#11	1#8
	B4	230	510	3#6	2#6	190	410	1#11	1#8
Column	C5	250	350	8#4		250	350	8#4	
	C6	250	350	8#4		250	350	8#4	
	C7	250	350	8#4		250	350	8#4	
	C8	250	250	6#5		250	350	4#7	
	C9	250	350	8#4		250	350	8#4	
	C10	250	350	8#4		250	350	8#4	
	C11	250	350	8#4		250	250	6#4	
	C12	250	350	8#4		250	250	6#4	
Best cost		3328.376 (€)				3220.842 (€)			



mg=mc=2 mg=mc=4

Figure 6. A diagram of optimized groups for the 2-bay and 4-story frame

4.2 Example 2: A three-bay and eight-story frame

This example is a three-bay and eight-story frame, as shown in Fig. 7. The distance between the bays is 7.5 m and the height of each story is 3.3 m. The beams are categorized in eight groups and the columns are categorized in sixteen groups, as shown in Table 7. This frame is optimized with 1, 2 and 4 groups for beams and columns.

Table 7: Member grouping for the 3-bay 8-story frame

Group	Member	Group	Member	Group	Member
B1	1,2,3	C9	25,28	C17	41,44
B2	4,5,6	C10	26,27	C18	42,43
B3	7,8,9	C11	29,32	C19	45,48
B4	10,11,12	C12	30,31	C20	46,47
B5	13,14,15	C13	33,36	C21	49,52
B6	16,17,18	C14	34,35	C22	50,51
B7	19,20,21	C15	37,40	C23	53,56
B8	22,23,24	C16	38,39	C24	54,55

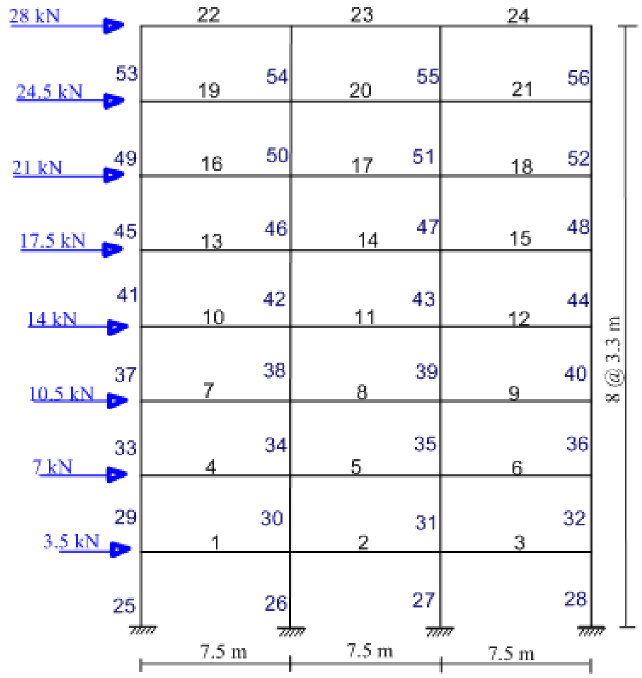


Figure 7. Geometry of the eight-story frame

According to Table 8 the results show that, where the number of groups for beams and columns is limited to four, the reduction of optimal cost in the automatic grouping method compared to the manual grouping method is 4.7%. Where the number of groups for beams and columns is limited to two groups, the cost is reduced by 1.5%. In Fig. 8, a comparison of the optimal cost of manual and automatic grouping is presented. Table 9 and Fig. 9 present the results of optimization and the allocation of beams and columns for groups based on the automatic grouping method. In this example, the stopping criterion for the algorithm is 3000 iterations.

Table 8: Summary of the optimization result for the 3-bay 8-story frame with and without automatic grouping procedure

Grouping procedure	**Upper limit of groups**	**Cost (€)**	**ndcs**	**The parameter of algorithm**	
				pro	pop
Automatic grouping	mg=mc=2	20578.49	4	24	0.75
	mg=mc=4	19528.38	6	24	0.7
manual grouping	mg=mc=2	20883.8	4	24	0.5
	mg=mc=4	20453.61	8	18	0.25

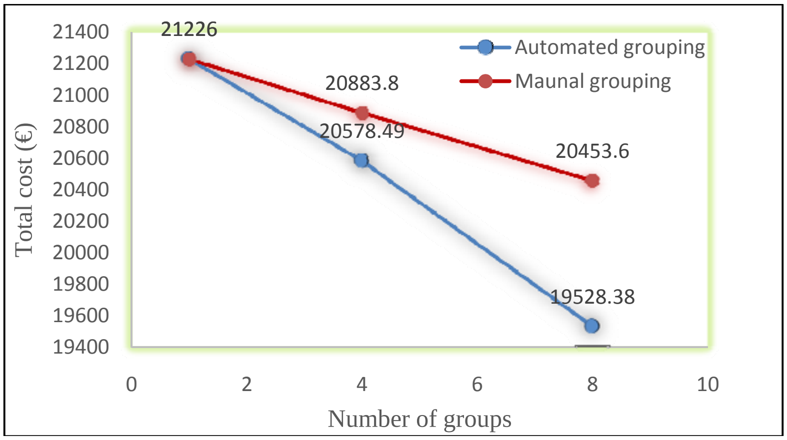


Figure 8. Comparison of the results of the optimization for the 3-bay 8-story frame with and without automatic grouping in variable number of groups

Table 9: Assigning the members to groups by using automatic grouping for 3-bay and 8-story frame

		mg=2 mc=2				mg=4 mc=4			
	Group	**b (mm)**	**h (mm)**	**A_s top**	**A_s bottom**	**b (mm)**	**h (mm)**	**A_s top**	**A_s bottom**
Beam	B1	300	550	3#9	2#7	300	500	4#8	6#4
	B2	300	550	3#9	2#7	300	500	4#8	6#4
	B3	300	550	3#9	2#7	300	500	4#8	6#4
	B4	300	550	3#9	2#7	300	500	4#8	6#4
	B5	300	550	3#9	2#7	300	500	4#8	6#4
	B6	300	550	3#9	2#7	300	550	3#8	3#6
	B7	300	500	3#8	6#4	300	550	3#8	3#6
	B8	300	550	3#9	2#7	300	550	3#8	3#6
Column	C9	300	500	8#6		300	500	8#5	
	C10	400	500	18#4		300	700	8#6	
	C11	300	500	8#6		300	500	8#5	
	C12	400	500	18#4		300	700	8#6	
	C13	300	500	8#6		300	500	8#5	
	C14	300	500	8#6		300	700	8#6	
	C15	300	500	8#6		300	500	8#5	
	C16	300	500	8#6		300	500	8#5	
	C17	300	500	8#6		300	500	8#5	
	C18	300	500	8#6		300	500	8#5	
	C19	300	500	8#6		300	500	8#5	
	C20	300	500	8#6		300	300	8#4	
	C21	300	500	8#6		300	500	8#5	
	C22	300	500	8#6		300	300	8#4	
	C23	300	500	8#6		300	450	4#9	
	C24	300	500	8#6		300	300	8#4	
Best Cost		20578.49 (€)				19528.38 (€)			

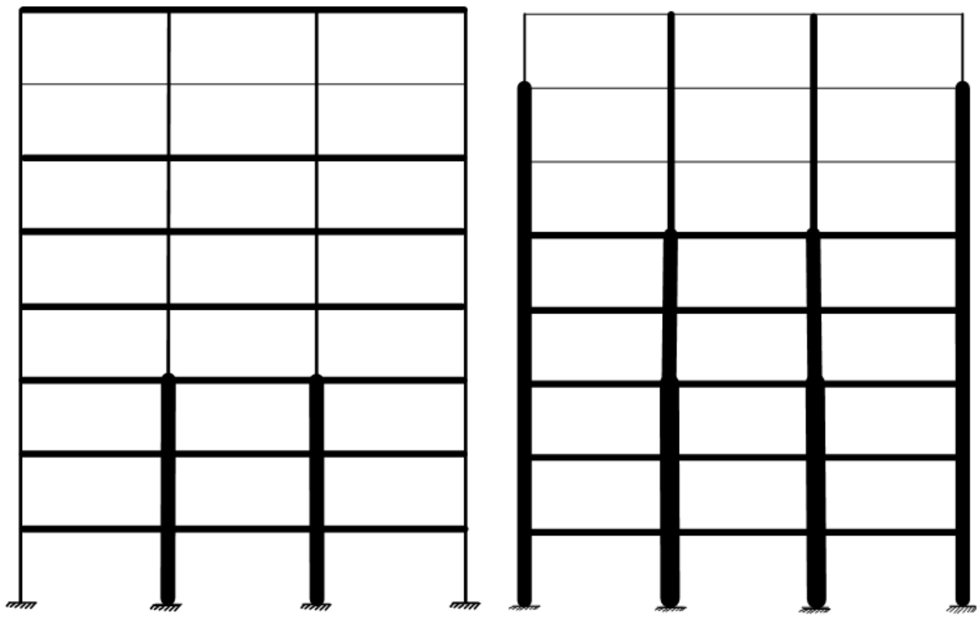


Fig. 9. A diagram of optimized groups for the 3-bay 8-story frame

4.3 Example 3: A three-bay and twelve-story frame

The third example is a three-bay and twelve-story frame whose geometry is illustrated in Fig. 10. The frame is optimized with number of groups 1, 4 and 6 for beams and columns. As shown in Table 10, the beams and columns are linked in 36 groups. In this example, 3000 iterations are selected as the stopping criterion of the algorithm. The parameters used for the algorithm as well as the optimal cost for both grouping are presented in Table 11. The results show that using the automated grouping process, the optimal cost has been reduced by about 3%. For comparison, the optimal cost of manual grouping and automatic grouping are depicted in Fig. 11. Table 12 and Fig. 12 present the results of optimization and the allocation of beams and columns for automatic grouping.

Table 10: Member grouping for the 3-bay and 12-story frame

Group	Member	Group	Member	Group	Member
B1	1,2,3	C13	37,40	C25	61,64
B2	4,5,6	C14	38,39	C26	62,63
B3	7,8,9	C15	41,44	C27	65,68
B4	10,11,12	C16	42,43	C28	66,67
B5	13,14,15	C17	45,48	C29	69,72
B6	16,17,18	C18	46,47	C30	70,71
B7	19,20,21	C19	49,52	C31	73,76
B8	22,23,24	C20	50,51	C32	74,75

B9	25,26,27	C21	53,56	C33	77,80
B10	28,29,30	C22	54,55	C34	78,79
B11	31,32,33	C23	57,60	C35	81,84
B12	34,35,36	C24	58,59	C36	82,83

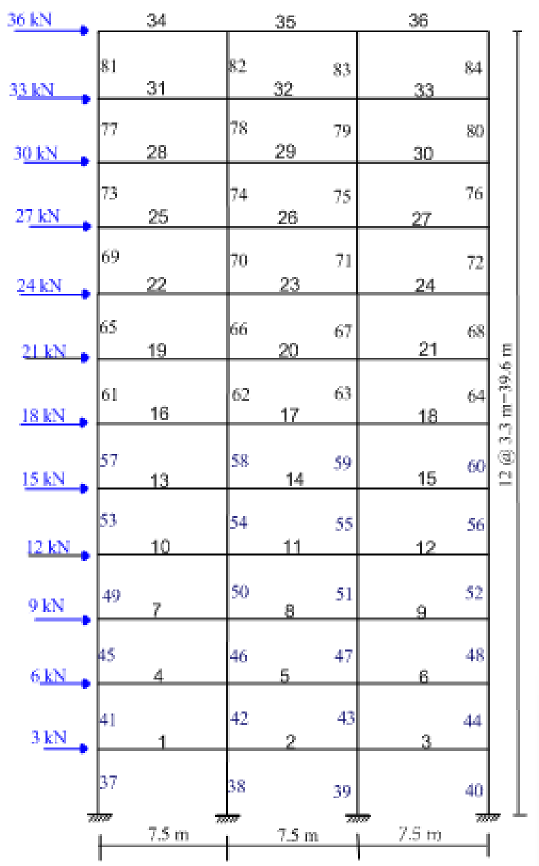


Figure 10. The geometry of the 3-bay and 12-story frame

Table 11: Summary of the optimization result for the 3-bay 12-story frame with and without automatic grouping procedure

Grouping procedure	**Upper limit of groups**	**Cost (€)**	**ndcs**	**The parameter of algorithm**	
				pro	pop
Automatic grouping	mg=mc=4	33748	7	24	0.65
	mg=mc=6	33341	9	24	0.4
manual grouping	mg=mc=4	34712	8	24	0.65
	mg=mc=6	34333	12	18	0.75

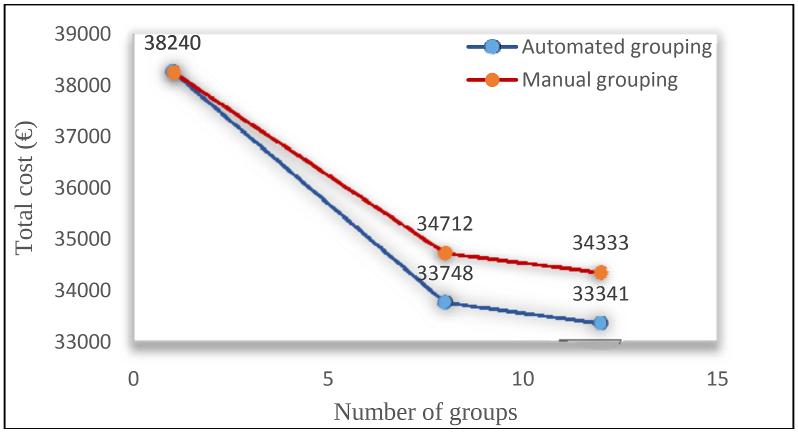


Figure 11. Comparison of the results of the optimization for the 3-bay 12-story frame with and without automatic grouping in variable number of groups

Table 12: Assigning the members to groups by using automatic grouping for 3-bay 12-story frame

		mg=4 mc=4				mg=6 mc=6			
	Group	**b (mm)**	**h (mm)**	**A_s top**	**A_s bottom**	**b (mm)**	**h (mm)**	**A_s top**	**A_s bottom**
Beam	B1	300	600	3#4	6#10	300	600	4#8	5#5
	B2	300	600	3#4	6#10	300	600	3#10	4#5
	B3	300	600	3#4	6#10	300	600	3#10	4#5
	B4	300	600	3#4	6#10	300	600	4#8	5#5
	B5	300	600	3#4	6#10	300	600	4#8	5#5
	B6	300	600	3#4	6#10	300	600	4#8	5#5
	B7	450	450	9#5	2#10	300	550	4#8	2#8
	B8	450	450	9#5	2#10	300	550	4#8	2#8
	B9	450	450	9#5	2#10	300	550	4#8	2#8
	B10	300	550	4#7	6#4	300	550	4#8	2#8
	B11	300	550	4#7	6#4	300	550	3#8	5#5
	B12	300	550	4#7	6#4	300	550	3#8	5#5
Column	C13	300	700	6#9		300	700	8#6	
	C14	400	700	20#5		450	700	16#5	
	C15	300	700	6#9		300	700	8#6	
	C16	400	700	20#5		450	700	16#5	
	C17	300	700	6#9		300	700	8#6	
	C18	300	700	6#9		450	700	16#5	
	C19	300	700	6#9		300	700	8#6	
	C20	300	700	6#9		450	700	16#5	
	C21	300	700	6#9		300	700	8#6	
	C22	300	700	6#9		300	700	8#6	
	C23	300	500	6#7		300	550	6#6	
	C24	300	700	6#9		300	700	8#6	

	C25	300	700	6#9	300	550	6#6
	C26	300	700	6#9	300	550	6#6
	C27	300	700	6#9	300	550	6#6
	C28	300	700	6#9	300	550	6#6
	C29	300	700	6#9	300	550	6#6
	C30	300	700	6#9	300	550	6#6
	C31	300	700	6#9	300	550	6#6
	C32	300	350	4#7	300	550	6#6
	C33	300	700	6#9	300	550	6#6
	C34	300	350	4#7	300	300	6#5
	C35	300	700	6#9	300	500	6#7
	C36	300	350	4#7	300	300	6#5
Best Cost		33748.46 (€)				33341.31 (€)	

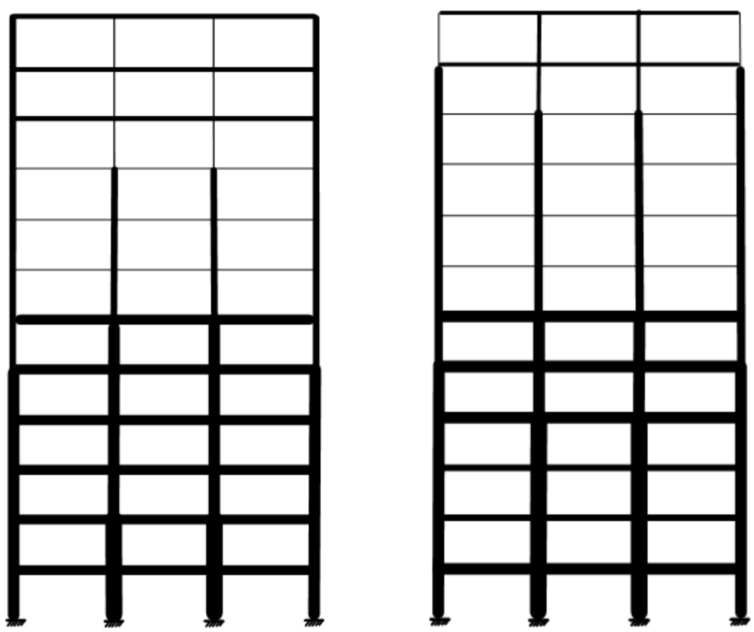


Figure 12. A diagram of optimized groups for 3-bay 12-story frame

5. CONCLUDING REMARKS

In optimizing reinforced concrete structures, the optimization objectives usually constitute the reduction of the cost of the concrete, steel and form wok. In which the beams and columns are grouped before design based on the designer's experience. The higher the number of groups for members, corresponds to lower optimal cost, but the cost of fabrication, welding, laboratory, checking, etc. which are not considered in cost function, increases. Using the automatic grouping technique, the beams and columns can be automatically grouped into the limited number of groups to reduce the optimum cost. In this study, the enhanced colliding bodies optimization algorithm is used to optimize the cost and automatic grouping of the beams and columns elements of the reinforced concrete structures. Here, the depth, width, number and diameter of bars in cross section of beams and columns are considered as variables. Furthermore, the number of groups for beams and columns in limited number are considered as variables, where the members of the groups are automatically determined. To investigate the process described, a 4-story frame under 12 types of load combination, 8-story and 12-story frames under 5 types of load combinations are considered. The optimal cost of the frames is determined for automatic grouping and manual grouping. The results show that in optimizing the cost of the reinforced concrete buildings by applying automatic grouping technique employing the ECBO algorithm, the optimal cost is reduced compared to the manual grouping. This decrease was up to 4.7% in the second example.

Compliance with ethical standards
Conflict of interest: No potential conflict of interest was reported by the authors.

REFERENCES

1. Akin A, Saka MP. Harmony search algorithm based optimum detailed design of reinforced concrete plane frames subject to ACI 318-05 provisions, *Comput Struct* 2015; **147**: 79-95. http://dx.doi.org/10.1016/j.compstruc.2014.10.003.
2. Tapao A, Cheerarot R. Optimal parameters and performance of artificial bee colony algorithm for minimum cost design of reinforced concrete frames, *Eng Struct* 2017;**151**: 802–20. https://doi.org/10.1016/j.engstruct.2017.08.059.
3. Esfandiari MJ, Urgessa GS, Sheikholarefin S, Dehghan Manshadi SH. Optimum design of 3D reinforced concrete frames using DMPSO algorithm, *Adv Eng Softw* 2018;**149**: 149-60. https://doi.org/10.1016/j.advengsoft.2017.09.007.
4. Barbosa HJC, Lemonge ACC. A genetic algorithm encoding for a class of cardinality constraints, *Proceedings of the Genetic and Evolutionary Computation Conference, GECCO*, 2005; pp. 1193–200. DOI: 10.1145/1068009.1068206.
5. Barbosa HJC, Lemonge ACC, Borges CCH. A genetic algorithm encoding for cardinality constraints and automatic variable linking in structural optimization, *Eng Struct* 2008;**30**: 3708–23. https://doi.org/10.1016/j.engstruct.2008.06.014.
6. Lemonge ACC, Barbosa HJC, Coutinho ALGA, Borges CCH.. Multiple cardinality constraints and automatic member grouping in the optimal design of steel framed structures, *Eng Struct* 2011;**33**: 433-44. https://doi.org/10.1016/j.engstruct.2010.10.026.
7. Angelo JS, Bernardino HS, Barbosa HJC. Ant colony approaches for multiobjective structural optimization problems with a cardinality constraint, *Adv Eng Softw* 2015; **80**:101-15 .https://doi.org/10.1016/j.advengsoft.2014.09.015.
8. Carvalho JPG, Lemonge ACC, Carvalho ÉCR, Hallak PH, Bernardino HS. Truss optimization with multiple frequency constraints and automatic member grouping, *Struct Multidiscip Optim* 2018;**57**(2): 547-77. DOI 10.1007/s00158-017-1761-x.

9. Kripka M, Medeiros GF, Lemonge ACC. Use of optimization for automatic grouping of beam cross-section dimensions in reinforced concrete building structures, *Eng Struct* 2015;??: 311-18. https://doi.org/10.1016/j.engstruct.2015.05.001.
10. Boscardin JT, Yepes V, Kripka M. Optimization of reinforced concrete building frames with automated grouping of columns, *Autom Construct* 2019;**15**: 331-40.
11. https://doi.org/10.1016/j.autcon.2019.04.024
12. Kaveh A, Mahdavi VR. Colliding bodies optimization: A novel meta-heuristic method, *Comput Struct* 2014; **139**(15): 18-27. https://doi.org/10.1016/j.compstruc.2014.04.005.
13. Kaveh A, Ilchi Ghazaan M. Enhanced colliding bodies optimization for design problems with continuous and discrete variables, *Adv Eng Softw* 2014;**77**: 66-75.
14. https://doi.org/10.1016/j.advengsoft.2014.08.003.
15. A. C. Institute. Building code requirements for structural concrete and commentary, ACI 318-08, 2008.
16. Kaveh A. *Advances in Metaheuristic Algorithms for Optimal Design of Structures*, Springer International Publishing, Switzerland, 2nd edition, 2017.
17. https://doi.org/10. 1007/978-3-319-05549-7
18. Kaveh A. *Applications of Metaheuristic Optimization Algorithms in Civil Engineering*, Springer International Publishing, Switzerland, 2017. https://doi.org/10.1007/978-3-319-48012-1.
19. Kaveh A, Bakhshpoori T. *Metaheuristics: Outlines, MATLAB Codes and Examples*, Springer, Switzerland, 2019.
20. Kaveh A, Izadifard RA, Mottaghi L. Optimal design of planar RC frames considering CO_2 emissions using ECBO, EVPS and PSO metaheuristic algorithms, *J Build Eng* 2019; **28**: 101014 https://doi.org/10.1016/j.jobe.2019.101014.
21. Camp CV, Huq F. CO_2 and cost optimization of reinforced concrete frames using a big bang-big crunch algorithm, *Eng Struct* 2013;**48**: 363-72. https://doi.org/10.1016/j.engstruct.2012.09.004.
22. Kaveh A, Ardalani S. Cost and CO_2 emission optimization of reinforced concrete frames using enhanced colliding bodies algorithm, *Asian J Civ Eng* 2016;**17**(6): 831-58.
23. Kaveh A, Sabzi O. Optimal design of reinforced concrete frames using big bang-big crunch algorithm, *Int J Civil Eng* 2012; **10**(3):189-200.
24. Kaveh A, Zakian P. Seismic design optimisation of RC moment frames and dual shear wall-frame structures via CSS algorithm, *Asian J Civil Eng* 2014;**15**(3): 435–65.
25. PEERS and OpenSEES. *Open System for Earthquake Engineering Simulation*, Pacific Earthquake Engineering Research Centre, University of California, Berkeley, 2012.
26. The Language of Technical Computing, MATLAB. Math Works Inc, 2016.