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Discrete cost optimization of composite floor system using social harmony search model

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ABSTRACT

This paper presents a social harmony search algorithm model for the cost optimization of composite floor system with discrete variables. The total cost function includes the costs of concrete, steel beam and shear studs. The design is based on AISC load and resistance factor design specifications and plastic design concepts. Here, six decision variables are considered for the objective function. In order to demonstrate the capabilities of the proposed model in optimizing composite floor system designs, two design examples taken from the literature are studied. It is shown that use of the presented model results in significant cost saving. Hence, it can be of practical value to structural designers. Also the proposed model is compared to the original harmony search, its recently developed variants, and other meta-heuristic algorithms to illustrate the superiority of the present method in convergence and leading to better solutions. In order to investigate the effects of beam spans and loadings on the cost optimization of composite floor system a parametric study is also conducted.

1. Introduction

Since the material cost is one of the major factors in the construction of a building, it is preferable to reduce it by minimizing the weight or volume of the structural system. Majority of articles are focused on the minimum weight design of structural systems, however, only a small fraction of these articles deal with the minimum total cost. Sarma and Adeli [1,2] published a review of the articles dealing with the cost optimization of concrete and steel structures, respectively. Jarmai and Farkas [3] discussed the cost calculation and the optimization of welded steel structures. Over the last three decades, few research articles have been published on cost optimization of composite floor system. Composite floors comprise of slabs and beams acting compositely together. A composite slab consists of profiled steel deck working together with in situ reinforced concrete. The deck not only acts as permanent formwork for the concrete, but also provides sufficient shear bond with the concrete, so that the two materials act compositely together. Composite floor beams are hot-rolled steel sections that act compositely with the slab. Composite action is normally achieved by welding shear studs through the steel decking and onto the top of the beams before pouring the concrete. The shear connectors provide sufficient longitudinal shear connection between the beam and the cured concrete so that they act together compositely. Composite slabs and beams together produce structurally a resource efficient flooring system for a range of applications. They are widely used in commercial multistory buildings because of their economy. The principal merit of steel-concrete composite construction lies in the utilization of the compressive strength of concrete slabs in conjunction with steel beams, in order to enhance the strength and stiffness of the steel girder. Composite floor systems are also stiffer, stronger and lighter than many other floor systems. This means that the weight and size of the primary structure and the foundations can often be reduced. Additionally, the principal advantage of composite floors compared to other systems is that of speed and ease of construction.

In practice, a composite beam is designed by a trial-and-error process to select the following parameters: (1) the concrete type expressed by its compressive strength and its unit weight, (2) the slab thickness, (3) the steel section size expressed by its cross-sectional area, and its steel grade expressed by its yield strength, (4) the strength of the shear connectors expressed by its shear resistance, and the number of shear connectors provided, and (5) the composite beam spacing. The design of composite beams is highly complicated. A beam may be fully or partially composite depending on the design parameters. The plastic deformation has to be considered in the case of the LRFD design code [4]. A reason of complexity is due to the fact that the location of the plastic neutral axis may lie within the web of the steel beam, the flange of the steel beam, or the concrete slab. All design parameters cannot be found

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simultaneously, since the value of a design parameter affects other values.

Because of the above mentioned advantages, and the difficulty of their design, in the last three decades researchers have been interested in optimal design of composite floor system using different optimization algorithms to decrease its total construction cost. The cost optimization of composite box girder bridge structures was presented by Surtees and Tordoff [5]. Zahn [6] discussed the economies of the LRFD design code versus the AISC allowable stress design code in the design of composite beams through the weight comparison of some 2500 composite designs using A36 steel. For short span beams in the range of 3.05 m and 6.1 m, Zahn discussed that the vibration serviceability constraint is the controlling design constraint using either one of the codes. The preliminary results of author indicated that the LRFD design code yielded a saving of 6–15% for span lengths ranging from 3.05 m to 13.7 m. Lorenz [7] studied the minimum cost design of composite beams based on the AISC–LRFD design code and argued that the real advantage of the AISC–LRFD concept could be realized in the minimum cost design. Bhatti [8] attempted to provide a standard optimization formulation and solving the problem approximately. However, his cost function includes the cost of the steel and field-installed shear studs only, neglecting the cost of concrete. Also, the cost optimization of composite highway bridge system was presented by Cohn and Werner [9]. Long et al. [10] presented a non-linear programming based optimization of cable-stayed bridges with composite superstructures. The defined cost objective function includes concrete, structural steel, reinforcement, cable stays and formworks costs. Kravanja and Šilih [11,12] introduced a non-linear programming optimization models and a mixed-integer non-linear programming approach for cost optimization of composite I beams, respectively. The optimization of composite floors, presented by Adeli and Kim [13], was carried out by employing the cost objective function, which contained the costs of concrete, steel beams and shear studs. The problem was formulated as a mixed integer-discrete nonlinear programming problem. The optimization based comparison between composite welded I beams and composite hollow-section trusses, introduced by Kravanja and Šilih [14], was accomplished by using the fixed cost parameter based objective functions, which comprised of the costs of concrete, steel sections, reinforcement, shear studs, anti-corrosion paint, fire protection paint, sheet-steel cutting costs, welding costs and the costs of the formworks. This objective function was also used by Klanšek and Kravanja [15] for the comparison of different composite systems for a pre-defined imposed load and a fixed steel price. A mixed-integer non-linear programming (MINLP) optimization approach to mechanical superstructures was presented by Kravanja et al. [16]. Klanšek and Kravanja [17,18] presented the cost optimization, comparison, and competitiveness between three different composite floor systems: composite beams produced from duo-symmetrical welded I sections, composite trusses formed from rolled channel sections and composite trusses made from cold formed hollow sections. The optimization was performed by the non-linear programming approach, NLP. Cost optimization of composite I beam floor system was developed by Klanšek and Kravanja [19]. Their objective function included the material, power consumption and labor cost items, required to handle all the necessary manufacturing costs of the composite I beam floor system and the structural optimization was performed by the nonlinear programming (NLP) approach taking into account design constraints defined according to Eurocodes. Senouci and Al-Ansari [20] presented the development of a genetic algorithm model for the cost optimization of composite beams. Their model was capable of generating optimal or near optimal design solutions that satisfy the constraints of the AISC–LRFD specifications. Their formulation includes the cost of concrete, steel beam, and shear studs. Designing composite floors using harmony search and an improved harmony search algorithms was performed by Kaveh and Shakouri [21]. Also, Kaveh and Masoudi [22] presented an ant colony optimization model for cost optimization of composite floor system based on the LRFD specification of the AISC.

Since, the design of composite floors is complicated and highly iterative and they are designed in a trial-and-error process, meta-heuristic algorithm-based models are efficient and effective methods for the cost optimizing of them because they can generate practical and optimum cost solutions. Hence, this study presents the discrete cost optimization of the composite floor system using a new version of harmony search algorithm that has been recently presented by Kaveh and Ahangaran [23] and entitled as “social harmony search algorithm”. Composite floor systems in this paper consist of a reinforced concrete slab and steel I beams and the formulation includes the cost of concrete, steel beams, and shear studs as well as, the design is based on AISC Load and Resistance Factor Design (LRFD) specifications and plastic design concepts. To demonstrate the capabilities of proposed model in generating optimal or near optimal design solutions two examples taken from the literature are utilized. Also, to illustrate the superiority of proposed model in quick convergence and finding better solutions compared to the original harmony search, its recently developed variants, and other meta-heuristic algorithms, a comparison of them was presented. A parametric study is also conducted to investigate the effects of beam spans and loadings on the cost optimization of composite floors.

The rest of this paper is organized as follows: Section 2 describes the model formulation. In this section design variables, objective function, and design constraints are introduced. In Section 3 after a brief review of harmony search algorithm, social harmony search is explained in detail and then, discrete cost optimization of composite floor system using the social harmony search model is presented. In Section 4, results of the experiments are presented and discussed. Section 5 is presented a parametric study to investigate the effects of beam spans and loadings on the cost optimization of composite floor system. Finally, Section 6 concludes the paper.

2. Model formulation

In order to formulate a robust optimization model that supports the cost minimization of composite floor, first we determine major decision variables affecting the design of composite floor and then formulate the objective function.

2.1. Decision variables

All decision variables that may have an impact on the cost optimization of composite floor are considered. The followings represent the decision variables related to each of concrete slab, steel beams, and the shear studs, separately.

For the concrete slab: the compressive strength of the concrete (f_c'), and the thickness of the slab (t_c).

For the steel beams section: the cross sectional area (A_s), the depth (d), the web thickness (t_w), the flange thickness (t_f), the flange width (b_f), the moment of inertia (I_s), the plastic modulus (Z_s), and the steel beams space in the composite floor (e). In order to reduce the complexity of the present model, the decision variables related to steel beam section except steel beams space, are combined into a single variable named as a steel section decision variable.

For the shear studs: the diameter (A_{sc}), and the number of shear studs for one beam (N_s).

Therefore, all decision variables that are considered in the present model can be simplified as follows:

Table 1
List of possible values for decision variables.

Concrete strength (f_c') MPa	Concrete slab thickness (t_c) mm	Steel section shape	Steel beams space (mm)	Shear stud diameter STD (mm)	Number of shear studs Ns
20	80	INP120	500	13	10
25	90	INP140	800	16	12
30	100	INP160	1000	19	14
35	110	INP180	1600	22	16
40	120	INP200	2000		18
	130	INP220	4000		20
	140	INP240			22
	150	INP260			24
	160	INP280			26
	170	INP300			28
	180	IPE120			30
	190	IPE140			32
	200	IPE160			34
		IPE180			36
		IPE200			38
		IPE220			40
		IPE240			42
		IPE270			44
		IPE300			46
		IPB120			48
		IPB140			50
		IPB160			
		IPB180			
		IPB200			
		IPB220			
		IPB240			
		IPB260			
		IPB280			
		IPB300			

X_1 = concrete compressive strength,
X_2 = concrete slab thickness,
X_3 = steel section shape,
X_4 = steel beam spacing,
X_5 = shear stud diameter, and
X_6 = number of shear studs for one beam.

A number of possible values for the six decision variables are listed in Table 1. Also, Fig. 1 shows the schematic view of a typical composite beam floor.

2.2. Objective function

A total cost function is defined in the following form:

$$C_t = C_c + C_s + C_{sd} \tag{1}$$

where C_c, C_s, and C_{sd} are the costs of concrete, steel beam and shear studs, respectively. They are defined as follows:

$$C_c = \gamma_c L W t_c C_c' \tag{2}$$

$$C_s = \left(\frac{W}{e} + 1\right) W_s L C_s' \tag{3}$$

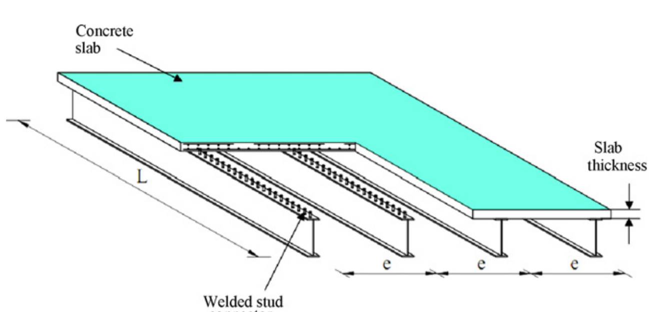

Fig. 1. Schematic view of a simple composite beam floor [19].

$$C_{sd} = N_s \left(\frac{W}{e} + 1\right) C_{sd}' \tag{4}$$

where γ_c is the unit weight of the concrete, L is the beam span length, W is width of the floor, t_c is the slab thickness, C_c' is the cost of concrete per unit volume, e is the steel beams space in composite floor, W_s is weight of the steel beam in length unit, C_s' is the cost of steel beam material per unit weight, N_s is the number of shear studs for one beam, and C_{sd}' is the cost of installing one shear stud including the material cost.

2.3. Design constraints

As mentioned before, the optimization of objective function is subjected to the constraints defined by the AISC–LRFD [4] specifications. These constraints are defined as follows:

(1) The bending moment capacity of the non-composite steel section must be checked to make sure that the steel beam can support temporary loads such as construction loads, the weight of the wet concrete, and its own weight,
(2) The bending moment capacity of the composite beam section must be checked to ensure the composite beam can carry all the dead and live loads,
(3) Deflection of composite beam, and
(4) Shear connector placement and spacing.

It should be noted that, the first constraint is considered when the composite floor is constructed without shores. The above mentioned constraints are described briefly in next three subsections.

2.3.1. Flexural strength constraints

The ultimate bending moment must be less than or equal to the nominal flexural strength multiplied by the resistance factor (ϕ_b). Two cases must be considered. First, the moment capacity of the non-composite steel section must be checked to make sure that the steel beam can support temporary loads such as construction loads,

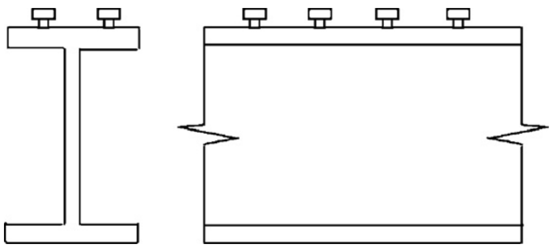

Fig. 2. Shear stud [13].

the weight of the wet concrete, and its own weight. This constraint is defined as:

$$M_{u\text{-}non\text{-}composite} \leq \phi_b M_{n\text{-}non\text{-}composite}, \quad \phi_b = 0.9 \tag{5}$$

where $M_{u\text{-}non\text{-}composite}$ is the ultimate moment due to the wet concrete weight, the temporary loads, and the own weight of the steel section, and $M_{n\text{-}non\text{-}composite}$ is the nominal moment capacity of the non-composite steel section.

Second, the moment capacity of the composite section to carry all the required dead and live loads must be checked, as expressed by the following constraint:

$$M_{u\text{-}composite} \leq \phi_b M_{n\text{-}composite}, \quad \phi_b = 0.85 \tag{6}$$

where $M_{u\text{-}composite}$ is the ultimate moment due to dead and live loads, and $M_{n\text{-}composite}$ is the nominal moment capacity of the composite beam.

2.3.2. Deflection constraints

As mentioned earlier, the deflection of composite floor depends on whether it is shored during the construction or not. The unshored construction is often the preferred method, since it is less labor-intensive and faster than the shored construction. For unshored composite beam, the deflection of the composite beam due to live load (Δ_{LL}) is limited to following value:

$$\Delta_{LL} = \frac{5w_{LL}L^4}{384E_s I_{tr}} \leq C_1 L \tag{7}$$

where w_{LL} is the service live load per unit length of the beam, E_s is the modulus of elasticity of the steel section. I_{tr} is the moment of inertia of transformed fully composite section, and C_1 is a coefficient ranging from 1/300 to 1/360. The moment of inertial of transformed composite section I_{tr} is based on the area of the steel beam and an equivalent concrete area.

2.3.3. Shear stud spacing constraints

Sufficient shear studs must be provided to prevent slippage along the interface of steel beam and concrete slab to ensure composite action. But, a minimum and a maximum spacing are defined by AISC–LRFD for center-to-center spacing of shear studs. The minimum center-to-center spacing of shear studs should not to be less than six times the diameter of the shear stud, and the maximum center-to-center spacing should not to be greater than eight times the total slab thickness.

$$6 \times \text{diameter of shear stud} \leq \text{shear studs spacing} \leq 8 \times \text{total slab thickness} \tag{8}$$

Fig. 2 shows a typical use of the shear studs.

3. Model implementation

As mentioned before, for cost optimization of composite floor system in this paper, the social harmony search algorithm is used. In this section, first a brief review of original harmony search algorithm is described then social harmony search algorithm is explained in more detail, and at the end, discrete cost optimization of composite floor system using the social harmony search model is presented.

3.1. Social harmony search algorithm

Recently, a new meta-heuristic optimization algorithm – harmony search (HS) with continuous design variables has been developed by Geem et al. [24]. However, HS can handle both discrete and continuous optimization problem but a new derivation of harmony search algorithm for discrete variables also has been presented by Geem [25]. Though HS is a relatively new meta-heuristic algorithm, its effectiveness and advantages have been demonstrated in various optimization problems [26]. It also has been applied to various structural optimization problems [27–34].

This meta-heuristic algorithm is conceptualized using the musical improvisation process of searching for a perfect state of harmony. Musicians seek to find pleasing harmony as determined by an aesthetic standard, just as the optimization process seeks to find a global optimum as determined by an objective function. The pitch of each musical instrument determines the aesthetic quality, just as the set of values assigned to each decision variable determine objective function value. Each musician improvises using three possible choices: (1) playing a note exactly from his or her memory; (2) playing a note in the vicinity of the previously selected note; (3) selecting a note randomly. These three choices of musicians were formalized into the harmony search algorithm's process by Geem et al. and the three options respectively become three rules of the algorithm as follows: harmony memory considering, pitch adjusting, and random selection. Fig. 3 shows the analogy between music improvisation and engineering optimization. To control the effect of the three mentioned rules in improvising a new harmony, Geem et al. used two parameters called HMCR and PAR. HMCR and PAR are fixed values with the range of 0.7–0.95 and 0.1–0.5, respectively. Algorithm with a probability of (1-HMCR) applies random selection rule, with probability of HMCR applies harmony consideration rule, and with probability of HMCR $\times$ PAR applies pitch adjusting rule to improvise a new harmony. In pitch adjusting section, algorithm adds $bw \times \varepsilon$ to the value that has been selected using memory considering rule. Here, ε is a random number from uniform distribution with the range of $[-1, 1]$, and bw is an fixed arbitrary distance bandwidth.

Although the HS has proven its ability in finding near global regions with in a reasonable time, it is comparatively inefficient in performing local search, because it uses fixed value for both PAR and bw and these parameters cannot be changed during the new improvisation. Hence, to eliminate the above mentioned drawback of the HS, some researchers such as: Mahdavi et al. [36] Taherinejad [37], Geem and Sim [38], and Kaveh and Ahangaran [23] recently have presented new variants of the HS and the latter is termed social harmony search algorithm. The serious drawback of the HS algorithm arising from pitch adjustment section is that it makes the algorithm unable to make a good balance between diversification and intensification that are two important features of the meta-heuristics algorithms. Social harmony search uses the principles of normal distribution to increase the HS operation. This method applies the normal distribution to update the position of each design variable of a new harmony found by the first rule of the HS (memory consideration) in every stage, to attain rapidly the feasible solution space. Normal distribution works as a global search in early iterations and as a local search in final iterations to improve HS to quickly converge and find better solutions. It makes an efficient balance between diversification and intensification during all generating of the algorithm feasible. The social HS adjusts the new harmony. Additionally, social HS simplifies the pitch adjusting rule because

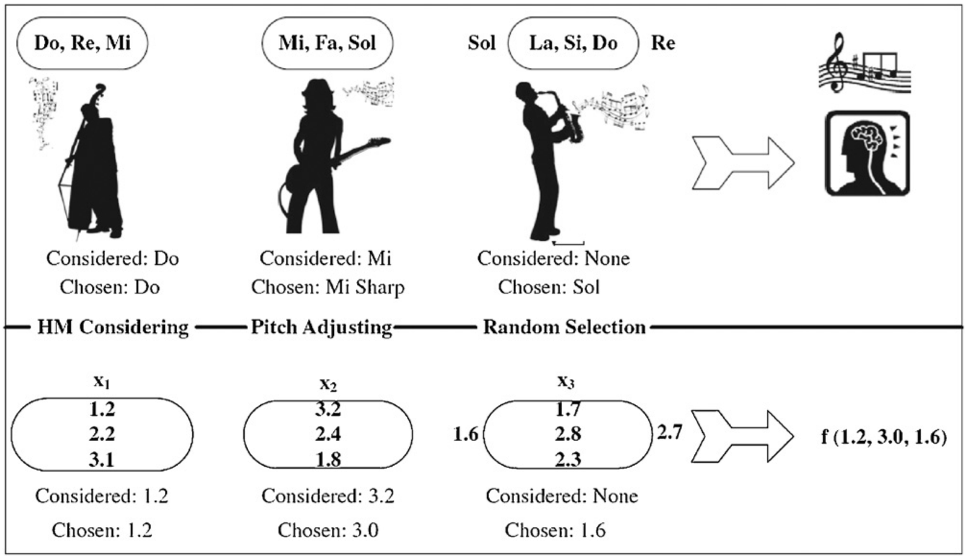

Fig. 3. Analogy between music improvisation and engineering optimization [35].

instead of using *bw* it uses the standard deviation of all values of the *i*th decision variables in the harmony memory and update them in each generation. This advantage makes the algorithm to find the new harmony with more social influence using experiments of all the harmonies. This method ensures that the HS algorithm achieve a good balance between diversification and intensification in the pitch adjustment rule.

To solve this discrete optimization problem using the social harmony search, some modifications are made. The social HS adjusts the new harmony for discrete optimization problems according to the following equation:

$$\mathrm{NINT}(N(x_i', \sigma_i')) \tag{11}$$

where x_i' is the selected value of the *i*th variable in the HM, σ_i' is the variance value of the *i*th variable in the HM, NINT(x) is the function which rounds each elements of x to the nearest permissible discrete value.

$N(x_i', \sigma_i')$ denotes a random number normally distributed with mean value x_i' and variance σ_i'.

$$\sigma_i' = \xi \times \sum_{j=1}^{\mathrm{HMS}} \frac{|x_i' - x_i^j|}{\mathrm{HMS} - 1} \tag{12}$$

where, HMS is the harmony memory size, x_i^j are all values of the *i*th decision variables in the HM. $1 \le j \le \mathrm{HMS}$ and $1 \le i \le N$, ξ is the fixed value to adjust the σ_i'.

Social HS for discrete optimization has exactly the same steps as that of the HS with the exception that step 3 being modified as follows:

while ($i \le$ number of variables decision (N))
  if (rand $\le$ HMCR) **then** (Memory consideration)
    $x_i' = x_i^j$, where $j \sim U(1, \ldots, \mathrm{HMS})$
    if (rand $\le$ PAR) **then** (Pitch adjustment)
      $x_i' = \mathrm{NINT}(N(x_i', \sigma_i'))$
    end if
  else (Random selection)
    $x_i' = LB_i + INT(r \times (UB_i - LB_i))$, where $r \sim U(0, 1)$
  end if
end while

3.2. Optimum design process using social HS model

The discrete cost optimization problem with constraints can be expressed as:

$$\begin{aligned} &\text{Minimize} && f(x) \\ &\text{Subject to} && g_r(x) \le 0, \quad r = 1, 2, \ldots, m \\ & && x_i \in D_i \qquad D_i(d_{i1}, d_{i2}, \ldots, d_{ini}), \quad i = 1, 2, \ldots, N \end{aligned} \tag{13}$$

where x is the real vector of design variables, $f(x)$ is the cost function, $g_r(x)$ is the *r*th inequality constraint, m is the total number of inequality constraints, N is the number of discrete design variables, D_i is the set of feasible discrete values for the *i*th variable, n_i is the number of feasible discrete values for the *i*th variable and d_{ik} is the *k*th discrete value for the *i*th variable. To solve this discrete optimization problem, we first translate the actual values of each variable into integer identifiers. Integer identifier for each variable begins with 1 and terminates with n_i (number of feasible discrete values for the *i*th variable). Algorithm chooses an integer identifier from feasible integer identifiers for each decision variable, then translates them into actual values of variables and then continues processes. In this paper, as mentioned earlier, to cost optimization of composite floors six decision variables are considered consisting of thickness of the concrete slab, center to center spacing of composite beams, steel beam shape, concrete compressive strength, shear stud size, and the number of shear studs. Also the constraints are handled by using fly-back mechanism. Compared to other constraint-handling techniques, this method is relatively simple and easy to implement [39].

The steps of the computation procedure of the discrete cost optimization of composite floor using the social harmony search model are described as follows:

(1) Select the value of algorithm parameters. (Including: HMS, HMCR, PAR, ξ)
(2) Translate the actual value of each decision variables into integer identifiers.
(3) Initialize the harmony memory (harmony memory is filled by integer identifiers of each decision variables).
(4) Improvise a new harmony using three rules: memory consideration, pitch adjustment and random selection.
(5) Translate the new harmony to actual value of each decision variable.

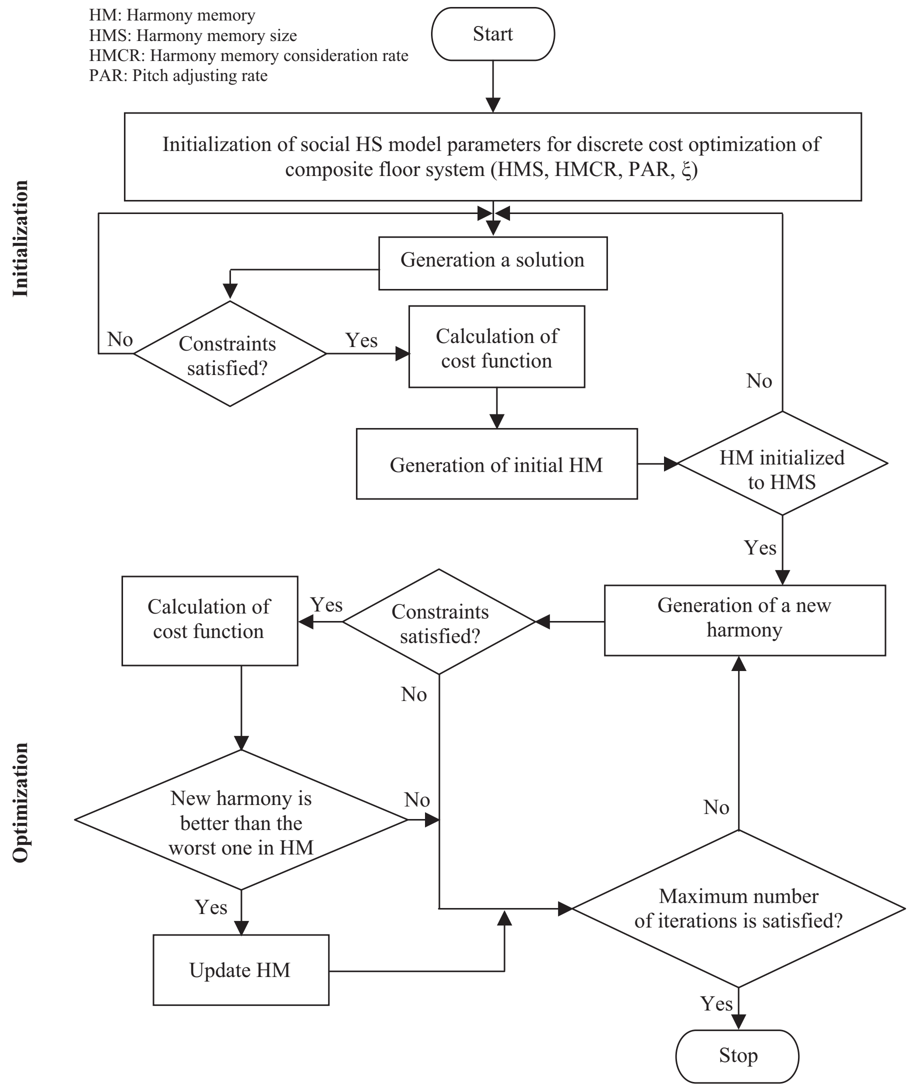

Fig. 4. Computational flowchart of the social harmony search model.

(6) Algorithm calculates the cost function if the new harmony satisfies the constraints.
(7) If the new cost function is better than the worst harmony vector in the harmony memory, the new harmony replaces the worst harmony by its own integer identifiers.
(8) Repeat steps 4–7 until the termination criterion is satisfied.

Note that, In harmony search, improved harmony search and the proposed method, we mapped discrete values of variables to values of (1, 2, . . ., M_i). M_i is the number of feasible values for the ith variable. The algorithms select one of the labels, and then it is mapped to the real value of corresponding variable again. These computational steps are implemented using a FORTRAN computer programming.

Fig. 4 shows the computation procedure of the composite floor design using the social harmony search model.

4. Numerical examples

In this study, we optimize the problem for one span and this span can be repeated in different directions to cover a ceiling. Also, a comparison of the proposed model with the standard harmony search (HS), its two new variants consisting of: improved harmony search (IHS), and highly reliable harmony search (HRHS), and ant colony optimization are presented to illustrate the superiority of the proposed model in quick convergence and finding better solutions.

Example 1. The floor is constructed with shores.

This example is the optimum cost design of a rectangular floor area with input design data summarized in Table 2. The data are taken from Kaveh and Shakouri [21].

In this example following constraints have to satisfy that defined by AISC–LRFD [4] specifications:

Table 2
Input design data for the composite floor design of Example 1.

Yield strength of steel beam	240 Mpa
Unit weight of the concrete	23.56 kN/m^3
Beam span length	6 m
Width of the floor	8 m
Dead load	3 kN/m^2
Live load	2 kN/m^2
C'_c	50 \$/m^3
C'_s	1 \$/kg
C'_{sd}	0.5 \$/stud

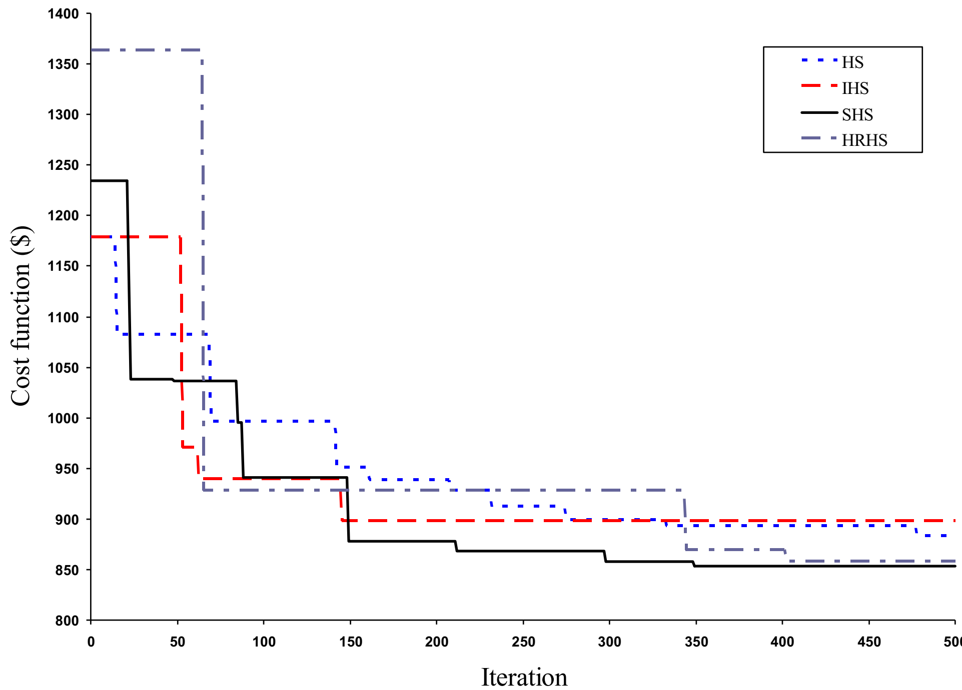

Fig. 5. Comparison of the convergence rates for the four algorithms (Example 1).

Table 3
Parameters for all methods used for Examples 1 and 2.

Methods	HMS	HMCR	PAR	PAR_{min}	PAR_{max}	Ξ
HS	30	0.9	0.45	–	–	–
HIS	30	0.85	–	0.35	0.99	–
HRHS	10	0.92	–	0.35	0.99	–
SHS	15	0.99	1	–	–	5

(1) Bending moment capacity of the composite beam section to ensure the composite beam can carry all the required dead and live loads,
(2) Deflection of composite beam,
(3) Shear connector placement and spacing.

Table 3 shows the parameters for all methods. These values were suggested by Kaveh and Shakouri [21], as well Kaveh and Masoudi [22].

In Table 4 optimum results of the five methods are compared, also costs saving of them are presented. t_c is the slab thickness, e is the steel beam space, f_c' is the concrete compressive strength, and A_{sc} and N_s are the diameter and shear studs number, respectively. As it can be seen, social HS leads to better results than other methods. Note that, social HS just requires 349 iterations to achieve the result shown in Table 4 but, other methods even, after 500 iterations cannot obtain social HS result. This result illustrates the superiority of social HS in quick convergence and finding better result compared to the HS, improved HS, and highly reliable HS. It should be mentioned that the ant colony optimization (ACO) result achieved after 100 iterations. Fig. 5 compares the convergence rate of the methods.

Example 2. The floor is constructed without shores.

Here the Example 1 is design without temporary shores. All data are the same as those of Example 1, but in this example more constraints have to be satisfied:

(1) Shear force and bending moment capacities of non-composite steel beam section to ensure that the steel beam can support the weight of the wet concrete and its own weight during the construction,
(2) Deflection of non-composite steel beam during construction,
(3) Bending moment capacity of the composite beam section to ensure that the composite beam can carry all the required dead and live loads,
(4) Deflection of composite beam,
(5) Shear connector placement and spacing.

As shown in Table 5, Social HS again achieve better results than other methods. Notice that social HS just needs 267 iterations to achieve this result but other methods after 500 iterations cannot gain that result. Fig. 6 compares the convergence rate of the methods. As shown in Fig. 6, social HS again outperformed other methods in convergence rate and in contrast to them has a better result, eventually.

Table 4
Optimal results for Example 1.

Models	Optimal design variables						Total cost ($)	% Cost saving
	t_c (cm)	e (cm)	Steel section	A_{sc} (mm)	N_s	f_c' (MPa)		
ACO [22]	8	200	INP200	12	18	20	1023.000	
IHS	11	200	IPE180	22	28	30	897.9999	12.22
HS	11	200	IPE180	19	22	35	882.9999	13.68
HRHS	11	200	IPE180	19	12	25	857.9999	16.13
SHS	11	200	IPE180	19	10	35	852.9999	16.62

Table 5
Optimal results for Example 2.

Models	Optimal design variables						Total cost ($)	% Cost saving
	t_c (cm)	e (cm)	Steel section	A_{sc} (mm)	N_s	f'_c (MPa)		
HS	8	400	INP240	19	34	25	894.6000	
IHS	8	400	INP240	22	22	35	876.6000	2.01
HRHS	8	400	INP240	19	22	35	876.6000	2.01
SHS	8	400	IPE270	22	16	30	865.8000	3.22

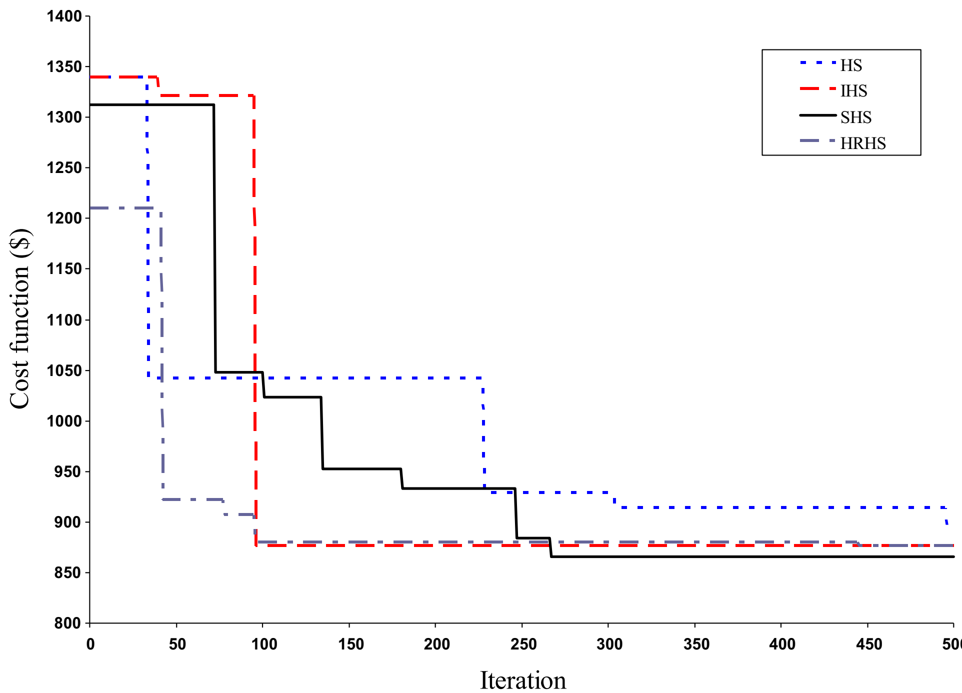

Fig. 6. Comparison of the convergence rates for the three algorithms (Example 2).

5. Parametric study

To investigate the effects of beam spans and loading on the cost minimization of the composite floor, a parametric study is also performed. In this section, since the concrete strength and slab thickness are selected as 35 MPa and 10 cm, respectively, the cost of concrete is fixed and only the cost of steel beam and shear studs are changed. Therefore, three decision variables are considered for this section. The values considered for the beam and loading are presented in Table 6. Other data are the same as those of Example 1 and the construction of the floor is with shores.

Design results achieved in the case study using the proposed model are presented in Table 7. As expected, to satisfy the strength and the deflection constraints the steel beam size increases by increasing both the beam span and the loads. Similarity, the size and the number of the studs increase with both the beam span and the loadings to satisfy the force and moment equilibrium.

Table 6
Parametric study.

Beam spacing (m)	Load combinations		Beam spans			
	Dead (kN/m^2)	Live (kN/m^2)	m	m	m	m
2	1	2	5	6	7	8
2	2	3	5	6	7	8
2	3	4	5	6	7	8

Table 7
Parametric study results.

Dead load (kN/m^2)	Live load (kN/m^2)	Beam span (m)	e (m)	f'_c (MPa)	t_c (cm)	Steel section	A_{sc} (mm)	N_s	Total cost ($)
1	2	5	2	35	10	INP140	22	10	582.500
		6				IPE180	22	10	828.999
		7				IPE220	22	12	1227.00
		8				IPE270	22	16	1804.00
2	3	5	2	35	10	IPE180	19	10	620.000
		6				IPE200	22	10	937.000
		7				IPE240	22	12	1384.50
		8				INP260	22	18	2041.00
3	4	5	2	35	10	IPE180	19	10	695.000
		6				IPE220	22	12	1056.00
		7				IPE270	22	16	1583.50
		8				INP280	22	26	2301.00

Table 8
Polynomial best-fit equations.

Dead load (kN/m^2)	Live load (kN/m^2)	Beam span (m)	Beam total cost ($)	Coefficient of determination (R^2)
1	2	L	$82.7L^2 - 668.94L + 1861.4$	1
2	3	L	$84.875L^2 - 632.33L + 1663.7$	0.9997
3	4	L	$89.125L^2 - 624.08L + 1588.4$	1

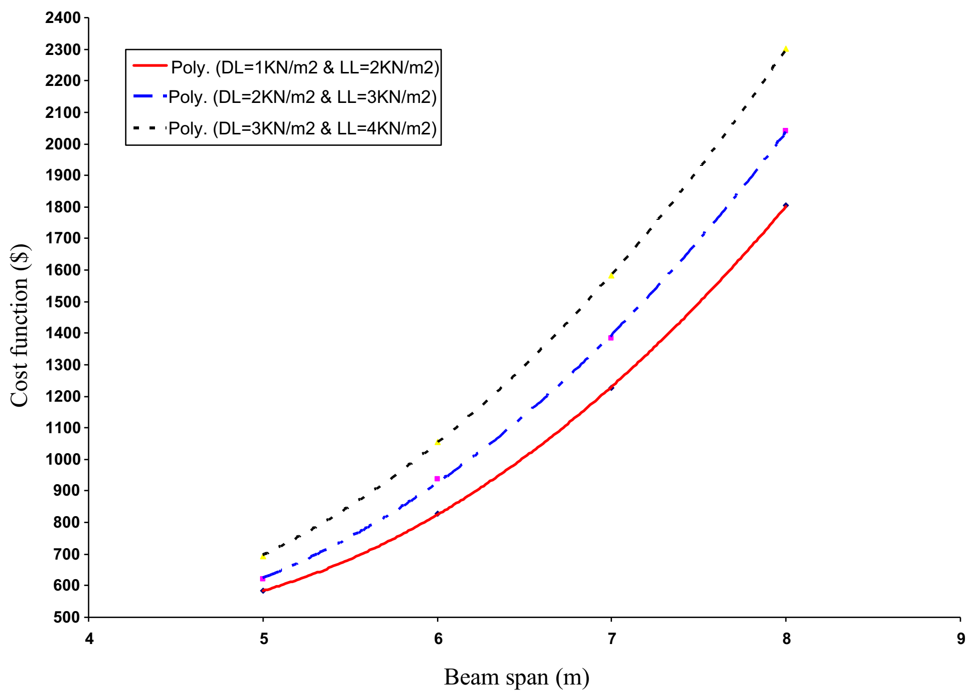

Fig. 7. Costs of optimal composite floor design.

Table 8 summarizes the second-order polynomial fits between the spans and the beam costs, which can be used to get an initial estimation of the total cost under a given span length and a given loading combination. The curves representing the variations between the total costs and the beam spans under three different loading combinations are shown in Fig. 7. The curves have same non-linear trend that increases with the beam span.

6. Conclusions

The paper is developed an economical social harmony search model to perform the discrete cost optimization of composite floors where design is based on AISC–LRFD specifications and plastic design concepts. The proposed model deals with the estimation of the construction cost of the composite floor which is proposed to be defined as the material costs, consisting of: concrete, steel beam and shear studs costs. The constraints are handled by using fly-back mechanism to ensure the optimum results to be in the feasible space. Since using the present model a significant cost saving is obtained, the structural designers will be able to generate optimal or near optimal solutions for various practical engineering problems using this model. The experimental results also reveal the superiority of the proposed model in quick convergence and finding better solutions compared to HS, and its new derivations. As mentioned earlier, the main aim of this paper is to show that for cost optimization of the practical engineering optimizations, the presented simple model can be utilized.

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