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Cost Optimization of Industrial Building using Genetic Algorithm

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Abstract— The study presents the simultaneous cost, topology and standard cross-section optimization of single storey industrial steel building structures. The considered structures are consisted from main portal frames, which are mutually connected with purlins. The optimization is performed by the Genetic algorithm (GA) approach.
The proposed algorithm minimizes the structure's material and labour costs, determines the optimal topology with the optimal number of portal frames and purlins as well as the optimal standard cross-sections of steel members.

Keywords— **Portal frames, Genetic algorithm, Optimization**

I. INTRODUCTION

Genetic algorithm method, which is one of the Artificial Intelligence Methods was the first proposed by Goldberg (1989). One of the first applications of genetic algorithm to civil engineering problems was done by Rajeev and Krishnamoorty (1992), and the method was applied three-bar truss system problem, in detail. In the study made by Ramasamy and Rajasekaran (1996), various truss configurations are designed using the expert system developed and the same configurations are optimized using Genetic Algorithm. Turgut, Gu¨ rel, and Arslan (1997) were made the optimization of a simple supported reinforced concrete beam by this method. Daloglu and Armutcu (1997) investigated the optimum design problem of truss systems via Genetic Algorithm. In this problem, constraints are tension, displacement and stability. In the studies of Wei, Liu, and Burns (1997), an algorithm was formed for time, cost, work optimization based on the principles of genetic algorithm. In the study of Friswell, Penny, and Garvey (1998) paper applies a Genetic Algorithm to the problem of damage detection using vibration data. The genetic algorithm is used to optimize the discrete damage location variables. In the paper of Rafiq and Southcombe (1998); for a biaxial column with a given set of design requirements (section size, axial load and bending about both axes of the column), it is shown how genetic algorithms conduct a global search to identity the optimal reinforcement bar size and bar detailing arrangement. In the study of Saka (1998), a genetic algorithm was presented for the optimum design of grillage systems to decide the cross-sectional properties of members from a standard set of universal beam sections. In Pezeshk, Camp, and Chen (2000) paper, they present a genetic algorithm-based optimization procedure for the design of 2D, geometrical nonlinear steel-framed structures. In Park, Lee, Han, and Vautrin (2003) paper, a multi-constraint optimization methodology for the design of composite laminated plates manufactured by Rasin Transfer Molding (RTM) process is presented. As design constraints, both the manufacturing process requirement and the structural requirement were considered. As an optimization method, the genetic algorithm was used. In the paper presented by Lepsˇ and Sˇ ejnoha (2003), an application of genetic algorithm based strategies to a class of optimization tasks associated with the design of steel reinforced concrete structures. In this particular case, the principle design objective is to minimize the total cost of a structure. In Sahab, Ashour, and Toropov (2005) paper, cost optimization of reinforced concrete slab buildings according to the British Code of Practice (BS8110) is presented. The objective function is the total cost of the building including the cost of floors, columns and foundation. Govindaraj and Ramasamy's (2005) paper present the application of genetic algorithm for the optimum detailed of reinforced concrete continuous beams based on Indian Standard specifications. The paper prepared by Castilho, El Debs, and Nicoletti (2007) describes the use of a modified GA as an optimization method in structural engineering for minimizing the production costs of slabs using precast prestressed concrete joists. The paper presented Saini, Sehgal, and Gambhir (2007) least-cost design of singly and doubly reinforced beams with uniformly distributed and concentrated load was done by incorporating actual self-weight of beam, parabolic stress block, moment-equilibrium and serviceability constraint besides other constraints.

II. OPTIMIZATION MODEL

A. Model

The single-storey industrial steel building structure is consisted from equal main portal frames, mutually connected with equal purlins (Fig. 1). Each portal frame is constructed from two columns and two beams. Purlins run continuously over the portal frames. Columns, beams and purlins are proposed to be built up from steel standard hot rolled Indian Standard Wide Flange Beam sections (ISWB sections) and Indian Standard Heavy Beam sections (ISHB sections, Fig. 2). The global building geometry (including the frame span L_f, the building length L_{Tot}, the column height H_C and the overhight f) is proposed to be fixing through the optimization. The vertical and horizontal bracing systems as well as the wall sheeting rails are not included in this optimization. The vertical and horizontal bracing systems as well as the wall sheeting rails are not included in this optimization.
The optimization model comprises input data, continuous and discrete binary variables, the structure's cost objective function, structural analysis constraints and logical constraints. The cost objective function is subjected to the set of structural analysis constraints.

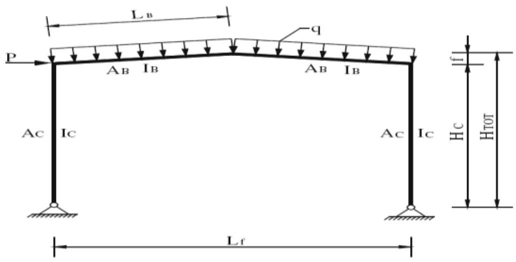
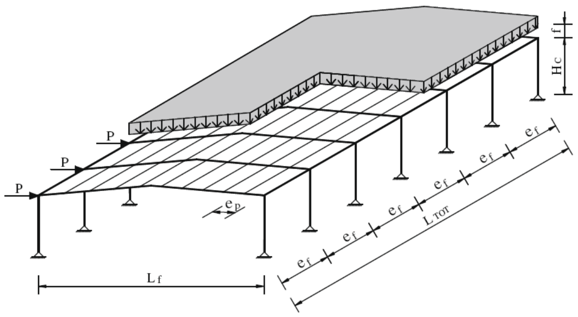


Fig.1 Single storey industrial steel building

Cost objective function is defined by Eq. (1). It comprises the material costs, the fabrication costs, the anti-corrosion and fire protection painting costs and the erection costs of the structure:

$$F(x)^{\#} = min\ COST = (n_{frame} * Vol_{frame} + n_{purlin} * Vol_{purlin}) * \rho * C_{mat} (1+C_{fabr}) + (n_{frame} * A_{frame} + n_{purlin} * A_{purlin}) * C_{paint} + (n_{frame} * C_{erect,frame} + n_{purlin} * C_{erect,purlin}) \quad (1)$$



The nomenclature of the variables is given in the appendix.

Fig.2.a Cross section of Indian standard section

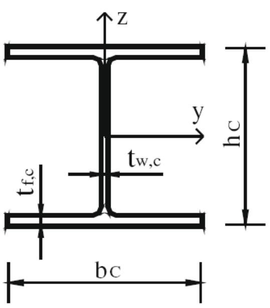


Fig. 2.b Elevation of Portal Frame

B.Constraints

Structural analysis constraints comprise the calculation of loads, internal forces and deflections as well as the checking the ultimate end serviceability limit state constraints. Considered is a single load case only, where the partial safety factors and combination of actions are defined according to IS Codes.

The optimization of the structure is performed under the combined effects of:

1. The self-weight of the structure (the line uniform load of columns, beams and purlins) and the weight of the roof g_r (the vertical surface load) plus
2. snows and the vertical wind w_v (the uniformly distributed vertical surface variable load) plus
3. the horizontal wind w_h (the horizontal force at the top of the columns P).

The horizontal concentrated load at the top of the columns P and the vertical uniformly distributed line load on beams and purlins, caused by the self-weight and the vertical wind, are calculated automatically through the optimization considering the calculated intermediate distance between the portal frames and purlins.

The *g(x) constraint* in the design problem, which is prepared using, IS 800-1984, and the normalized forms of these constraints are as given below:

a) The slenderness ratio constraint for compression member is given as:

$$\lambda_c \leq 250 \quad (2)$$

Where, $\lambda_c = 2\ H_c/r$; r = radius of gyration of section.

The result given below is obtained by normalizing expression:

$$g_{1,j}(x) = \lambda_c - 250 \leq 0 \quad (3)$$

b) The slenderness ratio constraint for beam member is given as:

$$\lambda_B \leq 180 \quad (4)$$

Where, $\lambda_B = L_B/r$; r = radius of gyration of section.

The result given below is obtained by normalizing expression ():

$$g_{2,j}(x) = \lambda_B - 180 \leq 0 \quad (5)$$

c) The slenderness ratio constraint for purlin is given as:

$$\lambda_p \leq 180 \quad (6)$$

where $\lambda_p = e_f/r$; r = radius of gyration of section.

The result given below is obtained by normalizing expression ():

$$g_{3,j}(x) = \lambda_p - 180 \leq 0 \quad (7)$$

d) The constraint for member subjected to axial compression and bending is given as:

if,

$$\frac{\sigma_{ac,cal}}{\sigma_{ac}} \leq 0.15 \quad (8)$$

then,

$$\frac{\sigma_{ac,cal}}{\sigma_{ac}} - \frac{\sigma_{bcx,cal}}{\sigma_{bcx}} - \frac{\sigma_{bcy,cal}}{\sigma_{bcy}} \leq 1 \quad (9)$$

where, $\sigma_{ac} = 0.66 \frac{f_{cc} * f_y}{[f_{cc}{}^n - f_y{}^n]^{1/n}}$ & $f_{cc} = \pi^2 E/\lambda^2$

The result given below is obtained by normalizing expression:

$$g_{4,j}(x) = \frac{\sigma_{ac,cal}}{\sigma_{ac}} - 0.15 \leq 0 \quad (10)$$

$$g_{5,j}(x) = \frac{\sigma_{ac,cal}}{\sigma_{ac}} + \frac{\sigma_{bcx,cal}}{\sigma_{bcx}} + \frac{\sigma_{bcy,cal}}{\sigma_{bcy}} - 1 \leq 0 \quad (11)$$

e) The bending stresses constraint for purlin is given as:

$$\sigma_{b,pur} \leq 0.8778\, f_y \quad (12)$$

The result given below is obtained by normalizing expression:

$$g_{6,j}(x) = \sigma_{b,pur} - 0.8778\, f_y \leq 0 \quad (13)$$

f) The maximum deflection constraint for beams is given as:

$$\delta_{max} \leq L_B/325 \quad (14)$$

The result given below is obtained by normalizing expression ():

$$g_{7,j}(x) = \delta_{max} - L_B/325 \leq 0 \quad (15)$$

C. Modification in objective function

It is necessary to transform constrained object function to unconstrained problem in order to obtain fitness criterion required by genetic algorithm. Therefore, unconstrained object function can be expressed for every individual by considering violation coefficient C, as given below

$$\Phi(x) = F(x)*(1+KC) \quad (16)$$

$\Phi(x)$ is an unconstrained function and its minimum value is determined by genetic algorithm. K is an auxiliary coefficient for increasing the effectiveness of constraint function C in the problems in which the constraints are forced, and for determining whether these types of systems are capable of passing to the next generation. K value is assumed as equal to 10, as used in the other problems of civil engineering (Rajeev & Krishnamoorty, 1992).

C is calculated as given below:

$$C = \sum_{i=1}^{m} c_i \quad (17)$$

Where m is constraint coefficient

If $g_{i,j}(x) > 0$, $c_i = g_{i,j}(x)$

If $g_{i,j}(x) <= 0$, $c_i = 0$

After being calculated for every individual, the unconstrained object function $\Phi(x)$ is required to be changed to fitness values having the fittest. According to Goldberg (1989)'s proposal, for minimization problems, $\Phi(x)$ should be subtracted from a large fixed-value; so that all fitness values will become positive and fitness values of the individuals will be obtained depending on their effective values. This fixed value is obtained by summing up maximum and minimum values of $\Phi(x)$ in a table. The calculation for fitness degree is made as follows:

$$F_{udi} = [\Phi_i(x)_{max} + \Phi_i(x)_{min}] - \Phi_i(x) \quad (18)$$

F_{udi}, here, represents fitness degree of individual i; and index i represents an individual in a generation. $\Phi_i(x)_{max}$ and $\Phi_i(x)_{min}$ represent maximum and minimum values of unconstrained $\Phi(x)$ function in a population consisting of all the individuals, respectively.

Fitness factor of each individual is calculated by F_{udi}/F_{av}. Here

$$F_{udi} = \sum F_{av}/n \quad (19)$$

Where, n is the total number of individuals in the population. By considering this ratio, it is decided for either destroying of each individual, or copying of each individual to mating pool for the next generation.

The next step is creating a new population for the next generation. Having created the mating pool individuals randomly mate there and crossover operators are applied. Thus, the next generation takes place. Then, the operation is repeated by replacing new generation instead of old generation. This operation is repeated until 80% or 85% of new generation constituted from the same individual, and this individual found represents optimum solution.

III. Numerical Example

The study presents an example of the simultaneous cost, topology and standard dimension optimization of a single-storey industrial steel building. The building is 24 m wide, 82 m long and 5.5 m high (Fig. 3). The over height of the frame beam is 0.45 m.

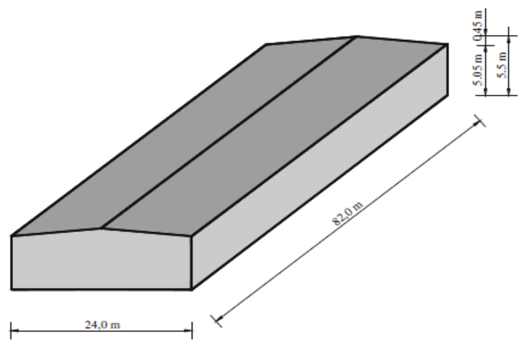


Fig.3. Global geometry of single story industrial steel building

A. Load, Material and geometric specifications of the structure

The portal frame was subjected to the self-weight (g) of structure and roof, to the uniformly distributed variable load of snow (s) and vertical wind (w_v) as well as to the concentrated variable load (P) at the top of columns (caused by the horizontal wind w_h). The weight of the roof was g_r = 0.21 kN/m^2 (including loads of GI sheeting = 0.085 kN/ m^2, fixings = 0.025 kN/m^2 and services = 0.1 kN/m^2), Snow s = 2.20 kN/m^2, the vertical wind w_v = 0.12 kN/m^2 and the horizontal wind, w_h = 0.45 kN/m^2 were defined in the model input data as the variable loads.

The material used was steel Fe 410. The yield strength of the steel f_y is 230 MPa, the density of steel ρ is 7850 kg/m^3, the elastic modulus of steel E is 2 X 10^5 MPa and the shear modulus G is 0.769 X 10^5 MPa (As per IS 2062 and IS 800).

An industrial building superstructure was generated in which all possible constructional variations were embedded by 30 portal frame alternatives, 10 various purlin alternatives and a variation of different standard cross-sections. In this way, the superstructure consisted of n possible number of portal frames, n∈N, N = {1,2,3,. . .,30}, and 10 various even (2m) number of purlins, m∈M, M = {1,2,3,. . .,10}, which gave 30 X 10 = 300 different topology alternatives. In addition, the superstructure comprised also 30 different standard hot rolled Indian Standard wide flange I sections and heavy weight beams, i.e. ISWB sections & ISHB sections (from ISWB 150 to ISWB 600 & ISHB 150 to ISHB 450) for each column, beam and purlin separately.

B. Creating population pool

In this problem, chromosomes are constituted via binary coding systems. Since the design variables are discrete, it is necessary to prepare a pool of possible design variables, which may be assumed as design variables.

The design variables pool considered is as follows: (As per SP 6 part 1)

S = {ISWB 150, ISWB 175, ISWB 200, ISWB 225, ISWB 250, ISWB 300, ISWB 350, ISWB 400, ISWB 450, ISWB 500, ISWB 550, ISWB 600, ISHB 150, ISHB 200, ISHB 225, ISHB 250, ISHB 300, ISHB 350, ISHB 400, ISHB 450} OR in terms of area of the sections (cm^2) involved in population pool.

S={21.67, 28.11, 39.71, 43.25, 52.05, 61.33, 72.50, 85.01, 101.15, 121.22, 143.34, 170.38, 184.86, 34.48, 38.98, 44.08, 47.54, 50.94, 54.94, 59.66, 64.96, 69.71, 74.85, 80.25, 85.91, 92.21, 98.66, 104.66, 111.14, 117.89}.

The optimization was performed by the proposed Genetic algorithm optimization approach. The task of the optimization was to find the minimal structure's material and labour costs, the optimal topology with the optimal number of portal frames and purlins as well as the optimal standard cross-sections of members. The economical objective function included the material, anti-corrosion and fire (R 30) protection painting as well as assembling and erection costs of the structure. The economic data for the optimization are presented in Table 1. The fabrication costs of steel elements were calculated to be equal to 40% of the obtained material costs (C_{fabr} = 0.40).

Table 1 Economic Data for optimization (Courtesy MFF Hazira, L&T Powai)

C_{mat}	Price of the structural steel	1.05 EUR/kg
C_{paint}	Anti-corrosion resistant painting costs (R30)	22.5 EUR/m^2
$C_{erect,frame}$	Erection costs per 1 portal frame	450 EUR/frame
$C_{erect,purlin}$	Erection costs per 1 purlin	250 EUR/purlin

IV. Results and Discussion

The optimization was carried out by user-friendly version of GATOOL-BOX incorporated in MATLAB and computer program written in C-Language. Also to investigate the viability of using genetic algorithms for design optimization of structural systems and to show whether the developed program is compatible, a 10-bar truss (one problem taken from literature) is solved and the results obtained are compared to various other optimization algorithm.

Results obtained from running the program are as follows:

Table 2 Results obtained from C program

Topology		Cross sectional areas (cm^2)			Resultant cost (EUR)
Frames	Purlins	Beams	Columns	Purlins	
15	12	121.22	184.86	36.71	18315.5
13	16	121.22	184.86	36.71	17478.5
14	**12**	**121.22**	**184.86**	**36.71**	**17337.2**
14	14	121.22	184.86	36.71	17890.7

Table 3 Results obtained from MATLAB

Topology		Cross sectional areas (cm^2)			Resultant cost (EUR)
Frames	Purlins	Beams	Columns	Purlins	
13.2	11.6	121.22	184.86	36.71	16445.821
15	12	121.22	184.86	36.71	18315.477
13	16	121.22	184.86	36.71	17478.508
14	**12**	**121.22**	**184.86**	**36.71**	**17337.235**
14	14	121.22	184.86	36.71	17890.685

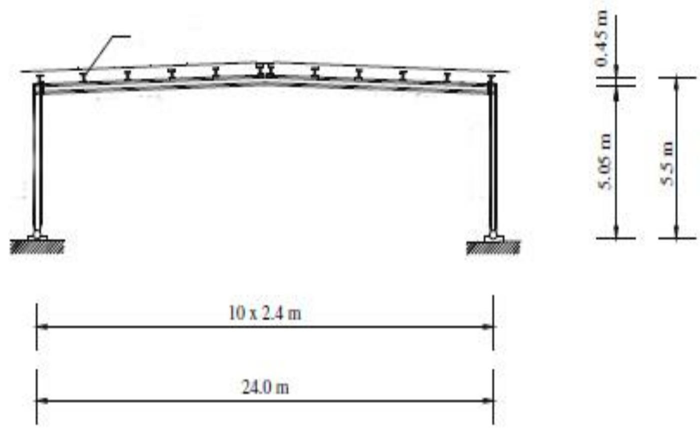


Fig 4 Optimum design of portal steel frame

The optimal result represented the obtained structure's minimal material and labour costs of 17337.235 EUR. The selling price may be at least twice higher. The solution also comprised the calculated optimal topology of 14 portal frames and 12 purlins, see Fig. 5, and the calculated optimal standard sections of columns (ISWB 600@145.1 kg/m), beams (ISWB 500@95.2 kg/m) and purlins (ISWB 200@28.8 kg/m), see Fig. 4. The obtained structure mass was 76120.34 kg.

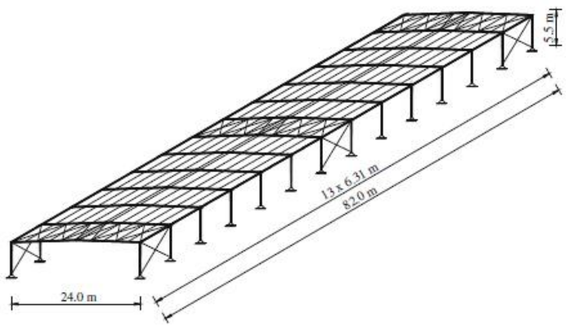


Fig. 5 Optimum design of single storey industrial steel building

The optimal result represented the obtained structure's minimal material and labour costs of 17337.235 EUR. The selling price may be at least twice higher. The solution also comprised the calculated optimal topology of 14 portal frames and 12 purlins, see Fig. 5, and the calculated optimal standard sections of columns (ISWB 600@145.1 kg/m), beams (ISWB 500@95.2 kg/m) and purlins (ISWB 200@28.8 kg/m), see Fig. 4. The obtained structure mass was 76120.34 kg.

V. Conclusion

In most of the problems encountered in civil engineering, the design variables are discrete. A few algorithms discussing the situation of discrete design variables were developed. Since genetic algorithm determines optimum solution by using discrete design variables, it can be said that it is a suitable method to provide solution for any problems encountered in civil engineering. The mathematical operations such as derivative, integral are not used in genetic algorithm, which makes this method easy to use.

With a view to the above facts, the main conclusions may be drawn as follows:

The main aim of the present paper is to obtain the simultaneous cost, topology and standard cross-section optimization of single-storey industrial steel building structures. A practical example of the simultaneous cost, topology and standard cross-section optimization of a 24 m wide and 82 m long single-storey industrial steel building structure is presented here. Beside the minimal structure's manufacturing costs, the optimal topology with the optimal number of portal frames and purlins as well as all standard cross-sections of steel elements have been obtained.

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REFERENCES

1. Camp C, Pezeshk S, Cao G. Design of framed structures using a genetic algorithm. Struct Optim ASCE 1996: 19–30.
2. Camp C, Shahram P, Cao G. Optimized design of two dimensional structures using a genetic algorithm. J Struct Eng ASCE 1998;124(5):551–9.
3. Goldberg D. Genetic algorithms in search, optimization and machine learning. Reading, MA: Addison–wesley; 1989.
4. Goldberg DE, Santani MP. Minimum weight design by genetic algorithm, engineering optimization via genetic algorithm. In: Proc Electr Comp 1986. p. 471–82.
5. Govindaraj, V., & Ramasamy, J. V. (2005). Optimum detailed design of reinforced concrete continuous beams using genetic algorithm. Computers and Structure, 84, 34–48.
6. Horridge JF, Morris LJ. Comparative costs of single storey steel framed structures. The Structural Engineers 1986;64A(7):177–81, London, UK.
7. Holland J. Adaptation in natural and artificial systems. Ann Arbor, MI: University of Michigan Press; 1975.
8. Kameshki E, Saka MP. Genetic algorithm based optimum bracing design of non-swaying tall plane frames. J Constr Steel Res 2001;57:1081–97.
9. Kameshki E, Saka MP. Optimum design of nonlinear steel frames with semi-rigid connections using a genetic algorithm. J Comput Struct 2001;79:1593–604.
10. Koza JR. Genetic programming. Cambridge, MA: MIT Press; 1992.
11. Lepsˇ, M., & Sˇ ejnoha, M. (2003). New approach to optimization of reinforced concrete beams. Computers and Structures, 81, 1957–1966.
12. Michalewicz Z. Genetic algorithm+data structure ¼ evolution programs. 3rd ed. New York: Springer-Verlag; 1996.
13. Park, C. H., Lee, W. I., Han, W. S., & Vautrin, A. (2003). Weight minimization of composite laminated plates with multiple constraints. Composites Science and Technology, 63, 1015–1026.
14. Pezeshk, S., Camp, C. V., & Chen, D. (2000). Design of nonlinear framed structures using genetic optimization. Journal of Structural Engineering, ASCE, 126, 382–388.
15. Rafiq, M. Y., & Southcombe, C. (1998). Genetic algorithm in optimal design and detailing of reinforced concrete biaxial columns supported by a declarative approach for capacity checking. Computers and Structures, 69, 443–457.
16. Rajeev S, Krishnamoorthy CS. Discrete optimization of structures using genetic algorithm. J Struct Eng ASCE 1992;118(5):1233–50.
17. Turgut, P., Gu¨ rel, M. A., & ve Arslan, A. (1997). Genetik Algoritma Ile Betonarme Bir Kirisin Optimum Tasarımı. In Prof. Dr. A. Rifat Yarar Sempozyumu (pp. 349–361). Istanbul: I.T.U¨ .
18. Wei, C., Liu, L., & Burns, S. C. (1997). Using genetic algorithm to solve construction time-cost trade off problems. Journal of Computing in Civil Engineering, 11, 184–189.

Appendix

Nomenclature: *Symbols*

L_f	Frame span	g_r	Mass of roof
L_{Tot}	Building length	w_v	Vertical wind load
H_c	Column height	w_h	Horizontal wind load
f	Over-height of the frame beam	C_{mat}	Price of the structural steel
f_y	Yield strength of structural steel	$C_{erect,frame}$	Erection price of the portal frame
E	Elastic modulus of steel	$C_{erect,purlin}$	Erection price of the purlin
G	Shear modulus of steel	C_{paint}	price of the anti-corrosion and fire protection painting
ρ	Density	C_{fabr}	Coefficient for

			calculating the fabrication costs
L_B	Length of beam	n_{frame}	Number of frames
e_f	Intermediate distance between portal frame	n_{purlin}	Number of purlins
e_p	Intermediate distance between purlins	σ_{ac}	Maximum permissible compressive stress in an axially loaded strut not subjected to bending
σ_{bc}	Maximum permissible compressive stress due to bending in a member not subjected to axial force	$\sigma_{ac,cal}$	Calculated average axial compressive stress
$\sigma_{bc,cal}$	Calculated compressive stress in a member due to bending about principal axis	A_{frame}	Surface area of each frame
A_{purlin}	Surface area of each purlin	Vol_{frame}	Volume of each frame
Vol_{purlin}	Volume of each purlin	δ_{max}	Maximum vertical deflection of beam or purlin
$\sigma_{b,purlin}$	Bending stresses in purlin	λ	Slenderness ratio