Application of Genetic Algorithm for Optimal Design of Portal Frame Structures

Onwuka D.O., Njoku F.C., Okorie D., and Ukachukwu O.C.

Department of Civil Engineering, Federal University of Technology Owerri, Imo State Nigeria

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ABSTRACT

This study developed and applied a MATLAB-based Genetic Algorithm (GA) program for the optimal design of steel portal frames with the aim of minimising cross-sectional area, weight, and cost. A single-span pitched-roof frame of 30 m span, 7 m eave height, and 3.5 m overheight was analysed, with variations in frame spacing from 6 m to 7.5 m, using S275 steel and BS 5950 design provisions. The GA optimisation consistently converged to efficient solutions, achieving 4–13 % cost savings and up to 10 % weight reduction compared with the empirical method. Results further showed that the column plastic modulus was approximately 50 % greater than that of the rafter, rafter depth was about span/55, and purlin depth was roughly one-quarter of the rafter depth. Although minor variations occurred due to stochastic algorithm behaviour, all runs produced results within the same performance bounds. The findings confirm the reliability of the developed GA framework as a practical and computationally efficient tool for designing cost-effective and structurally sound steel portal frames.

Keywords: Genetic algorithm, optimisation, portal frame, steel structures, cost efficiency, MATLAB

INTRODUCTION

Portal frames are among the most widely used structural systems for single-storey industrial, agricultural, and commercial buildings because they provide large clear spans with relatively low material cost, rapid construction, and simple detailing. Their efficiency in spanning 20 m–40 m without intermediate supports makes them essential for warehouses, factories, and retail halls worldwide (Salama et al., 2023). The growing demand for sustainable, economical, and high-performance building systems has intensified interest in optimisation-based design strategies that reduce both embodied carbon and overall project cost while satisfying strength, stability, and serviceability requirements (Salama et al., 2023; Huang et al., 2023).

Designing portal frames involves numerous discrete and continuous variables — member sizes, spacing, rafter pitch, haunch geometry, and connection stiffness — that interact non-linearly through code-based constraints. Conventional derivative-based or enumerative optimisation methods are often inefficient in such mixed design spaces: they are prone to local minima and computationally expensive for large search domains (Whitworth & Tsavdaridis, 2020). In contrast, population-based metaheuristic algorithms, particularly genetic algorithms (GAs), have proved highly effective because they do not rely on gradient information and can explore wide, non-convex feasible regions while accommodating discrete design variables (Greco et al., 2023; Stulpinas & Daniūnas, 2024).

Recent developments in structural optimisation have demonstrated the capability of GAs and their hybrid variants to achieve significant reductions in steel weight and cost. Studies integrating multi-objective formulations (such as NSGA-II or Pareto-based ranking) enable designers to balance conflicting objectives, including cost, stiffness, and environmental impact (Salama et al., 2023; Whitworth & Tsavdaridis, 2020). For instance, Salama et al. (2023) applied an embodied-carbon minimisation strategy to single-story steel portal frames, reporting reductions of about 14 %-26 % relative to prismatic-member configurations. Martins, Correia, Ljubinković, & Simões da Silva (2023) carried out cost optimisation of steel I-girder cross-sections using GA, showing substantial material savings. Meanwhile, Stulpinas & Daniūnas (2024) optimised thin-walled cold-formed portal-frame cross-sections via GA, achieving up to 22 % volume reduction in certain configurations.

Despite this progress, several challenges persist in practical GA implementation for portal-frame design. Many published models are limited to idealised boundary conditions, small span ranges (typically ≤ 25 m), or simplified loading scenarios, whereas real-world industrial buildings often demand longer spans, multi-bay configurations, and strict serviceability control. Moreover, convergence behaviour and parameter tuning — particularly population size, elite fraction, and mutation rate — significantly influence solution quality and computational efficiency (Greco et al., 2023). There is therefore a need for GA frameworks that are computationally efficient, code-compliant, and adaptable to standard hot-rolled steel sections used in professional practice.

Addressing these gaps, the present study develops a MATLAB-based GA program for the optimal design of hot-rolled steel portal frames. The program integrates structural analysis, geometric and material constraints, and code checks based on BS 5950. Its objective is to minimise cross-sectional area, weight, and total cost simultaneously while satisfying slenderness, stress, and deflection limits. The approach is applied to a pitched-roof, single-span frame with varying bay spacings between 6 m and 7.5 m, enabling evaluation of span-spacing effects on cost and weight efficiency. The paper presents the GA formulation and implementation, discusses sensitivity of results to algorithm parameters, and compares outcomes with both empirical design and previously published optimisation results.

MATERIALS AND METHODS

Materials

The materials used in applying the Genetic Algorithm (GA) to the optimal design of portal frames are summarised under two main components: the portal frames and the MATLAB GA software.

Portal Frames

The study considered portal frames with centre-to-centre spacings of 6 m, 6.5 m, 7 m, and 7.5 m, each having an eave height of 7 m and an overheight of 3.5 m. The arrangement of purlins and rafters remained consistent across all models, with frame spans of 30 m, 25 m, 22 m, and 20 m, respectively. The model portal frame adopted for analysis was that with a 6 m frame spacing and a 30 m span.

MATLAB GA Software

The optimisation process was executed using the Genetic Algorithm (GA) Toolbox in MATLAB, run on an HP 240 G7 Notebook PC equipped with 8 GB RAM and a 64-bit operating system. The MATLAB environment provided built-in functions for population generation, selection, crossover, mutation, and convergence analysis.

Methods

Developing a Program Designed to Optimise Portal Steel Structures

A MATLAB-based program was developed for the design and optimisation of portal frames using the elastic–plastic empirical design method. Frame parameters, represented by alphabetic symbols, were defined and input into the MATLAB workspace. The program was tested on different portal frame configurations, and the results closely matched those from conventional design methods.

Minimization Method Resulting to Cost-Effectiveness

The MATLAB GA toolbox was employed to optimise each portal frame configuration. Analysis data served as input, and the parameters were defined as fitness functions. The optimisation aimed to minimise cross-sectional area, weight, and cost, either individually or simultaneously. For single-objective runs, each parameter was treated as the fitness function in turn, while for multi-objective optimisation, the Pareto-based ranking approach by Fonseca and Fleming was applied to rank solutions by dominance and identify optimal trade-offs among objectives. The GA procedure involved defining the optimisation parameters, generating an initial population, evaluating fitness, and applying selection, crossover, and mutation operations until convergence or satisfaction of stopping criteria. Figure 1 shows the flowchart for the Genetic Algorithm used in the design.

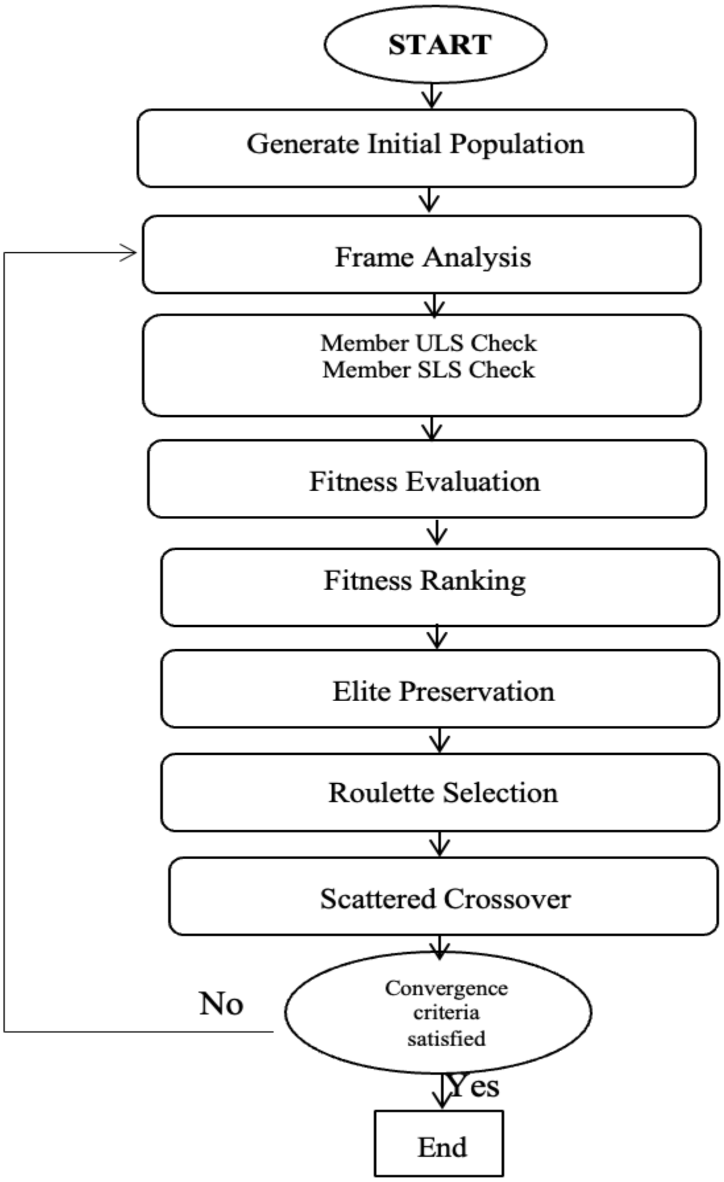

Figure 1: Flowchart of Genetic Algorithm

Design using Genetic Algorithm

A single-span, pitched-roof steel portal frame served as the model for weight and cost optimisation through standard cross-section dimensioning. The structure measures 30 m in span, 102 m in length, and 7 m in height, with an overheight of 3.5 m. Haunches were provided at the eaves and apex to reduce rafter depth and improve bending resistance (Salter, 2004). Purlins were spaced at 2.2 m centres, spanning a 6 m single bay. Fig 2 shows the steel portal frame structure

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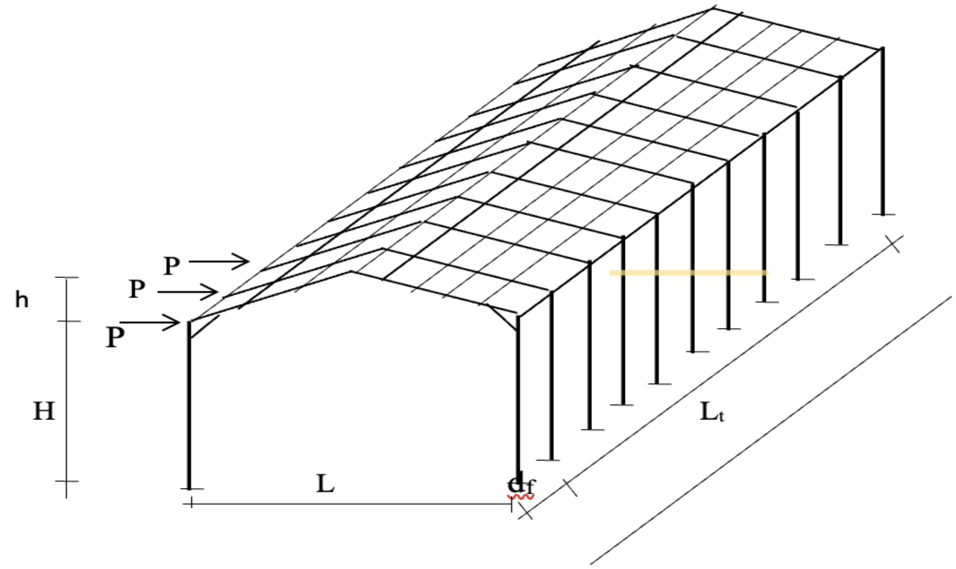

Fig 2 Steel Portal Frame Structure

The frame is constructed from steel grade S275 with a modulus of elasticity of 2.05 × 10^5 N/mm² and a density of 7850 kg/m³. The applied dead load and live load are 0.45 kN/m² and 0.75 kN/m², respectively, while a notional horizontal load equal to 5% of the total vertical load acts at the column top. Design was carried out in accordance with BS 5950, using hot-rolled standard I-sections for cross-sectional dimensions. Each frame comprises two universal columns and two universal beams per bay, with columns rigidly fixed at the base. These are illustrated in the figure below

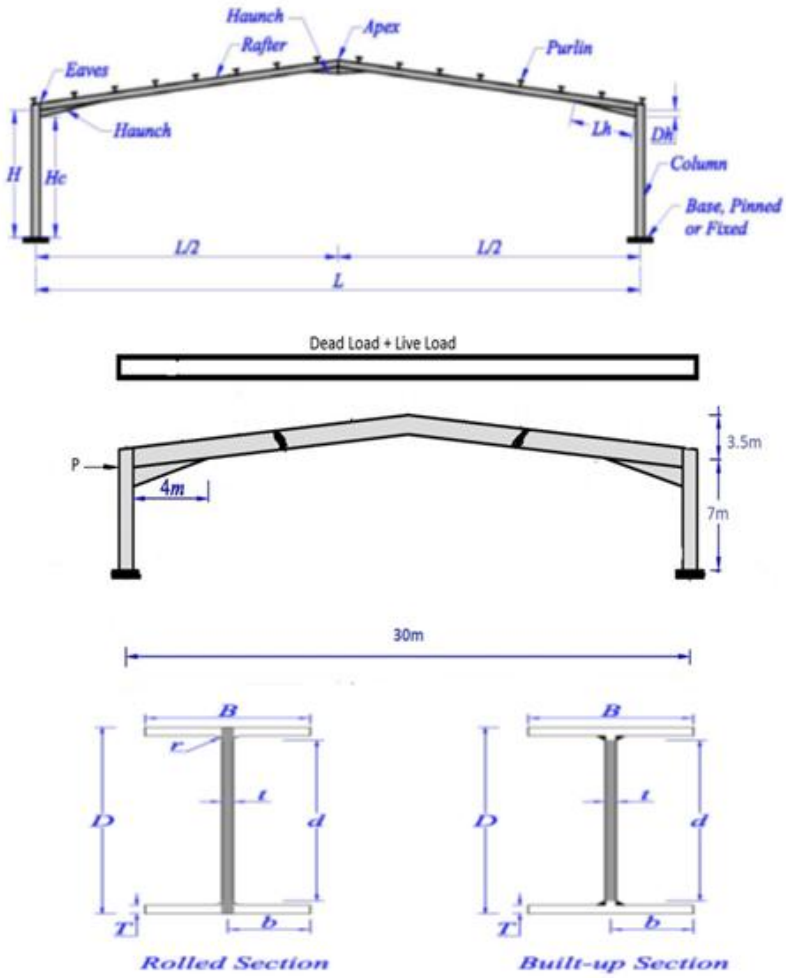

Fig 3: Frame details, loading and I cross-section

In this case, the ***objective function,*** *F(x)* is the cost which is a function of the weight minimization of the individual members of the frame.

$$F(x) = \min COST = (n_{purlin} * Vol_{purlin} + n_{beam} * Vol_{beam} + n_{column} * Vol_{column}) * \rho * C \quad (1)$$

subject to ultimate limit state and serviceability limit state ***constraints***:

i. ***Shear capacity:*** *Shear capacity, P_v of a selected section for structural members must be greater than the applied shear force, F_v:*

$$F_v \leq P_v = 0.6\, p_y\, A_v \quad (2)$$

For rolled I, H and channel sections, the shear area of the cross section A_v is:

$$A_v = tD \quad (3)$$

Hence,

$$F_v \leq P_v = 0.6\, p_y\, tD \quad (4)$$

ii. ***Moment capacity***: *Moment capacity of a selected section for structural members must be greater than the applied design moment.*

$$m \leq M_c = p_y S \quad (5)$$

iii. ***Local capacity:***

$$F/A_g P_c + Mx/Mcx + My/Mcy \leq 1 \quad (6)$$

iv. ***Deflection:***

For purlin, $\delta_{max} = 5wl_p^3/384EI \leq l_p/360$ (7)

$$5wl_p^3/384EI - l_p/360 \leq 0 \quad (8)$$

For beam(tension member), $\delta_{max} = 5wl_b^3/384EI \leq l_b/200$ (9)

$$5wl_b^3/384EI - l_b/200 \leq 0 \quad (10)$$

For column(compression member), $\delta_{max} = 5wl_c^3/384EI \leq l_c/200$ (11)

$$5wl_c^3/384EI - l_c/200 \leq 0 \quad (12)$$

v. ***Slenderness ratio:***

For purlin(tension member),slenderness ratio, $\lambda_p = l_p/r_y \leq 180$ (13)

$$\lambda_p = l_p/r_y - 180 \leq 0 \quad (14)$$

For beam(tension member),slenderness ratio, $\lambda_b = l_b/r_y \leq 250$ (15)

$$\lambda_b = l_b/r_y - 250 \leq 0 \quad (16)$$

For column(compression member),slenderness ratio, λ_c,

$$\lambda_c = l_c/r_y \leq 250 \quad (17)$$

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$\lambda_c = l_c/r_y - 250 \leq 0$ (18)

vi. Web Buckling Resistance:

$b/T \leq 9\mathcal{E}$ } for rolled section (19)

$d/t \leq 80\mathcal{E}$ (20)

vii. Sway Check:

a) The Span of the frame to the clear height of the column must not be greater than 5

i.e. $L/H \leq 5$ (21)

b) the height of the apex above the tops of the columns to the span of the frame must not exceed 0.25

i.e. $h/L \leq 0.25$ (22)

viii. The Bounds:

$4.0mm \leq t \leq 16mm$ (23)

$76mm \leq D \leq 910mm$ (24)

$76mm \leq B \leq 304mm$ (25)

$7.6mm \leq T \leq 24mm$ (26)

$16.2cm^2 \leq A \leq 286cm^2$ (27)

ix. $A_2 \leq 5A_1$ (28)

and

$A_3 \leq 1.4A_2$ (29)

Note: $A = (2*B*T) + (D-2T)*t$ (30)

and $Vol = A*l$ (31)

$M = \rho*V = \rho*A*l$ (32)

$r = [I/A]^{1/2}$ (33)

$C = 1.05$ (34)

$\mathcal{E} = [275/p_y]^{1/2}$ (35)

The beam and column sections were selected from standard hot-rolled Universal Beam (UB) profiles ranging from 127 × 76 × 13 mm to 914 × 305 × 224 mm, while purlins were chosen from joist sections ranging from 76 × 76 × 13 mm to 254 × 203 × 82 mm. The Genetic Algorithm first determined the optimal sectional areas (A), from which the volume (V), weight, and cost were subsequently computed using the defined equations. The optimisation was initially performed for frames with 6 m spacing, then repeated for 6.5 m, 7 m, and 7.5 m spacings using the same procedure.

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RESULTS AND DISCUSSIONS

Results

Table 1 illustrates the results obtained for the different portal frames considered using the program/ algorithm developed.

Table 1 Results obtained from portal frames analysis using the algorithm developed

Description		Portal Frames			
S/No		1	2	3	4
Specification	Span Length (m)	30	25	22	20
	Frame Spacing (m)	6	6.5	7	7.5
	Building Length (m)	102	117	126	135
	Frame Total Height	10.5	10.5	10.5	10.5
	Overheight	3.5	3.5	3.5	3.5
Length of each (m)	Purlin	6	6.5	7	7.5
	Rafter	15.4029	12.9808	11.5434	10.5948
	Column	7	7	7	7
Total Number in the Building	Purlin	255	230	207	191
	Rafter	36	38	38	38
	Column	36	38	38	38
Roof Load (KN/m)	Dead Load	2.7725	3.0375	3.3056	3.5757
	Life Load	4.5	4.8750	5.2500	5.6250
Design Load, w (KN/m)		11.0815	12.0525	13.0279	14.0060
Moment (KNm)	@ A or E	614.8711	438.5274	353.6030	306.0072
	@ B or D	-547.9963	-416.8227	-350.0729	-311.5595
	@ C	117.2428	97.1034	86.2742	79.9596
Reaction (KN)	@ A or E	166.2230	150.6562	143.3064	140.0605
Thrust (KN)	@ A or E	166.1239	122.1929	100.5251	88.2238
Notional Horizontal Load at each Column Top (KN)		0.8311	0.7533	0.7165	0.7003
Point Load on the Roof (KN)		332.4462	301.3124	286.6128	280.1210

Table 2 Result using GA showing the minimised sectional areas obtained

	Purlin (Joist)			Rafter or Beam UB			Column UB		
S/No	Area of section (cm^2)	Mass per Metre (kg/m)	Section Designation	Area of section (cm^2)	Mass per Metre (kg/m)	Section Designation	Area of section (cm^2)	Mass per Metre (kg/m)	Section Designation
1	**34.2**	26.9	127x114x27	**125**	98.3	457x191x98	**178**	139.9	610x229x140
2	**37.4**	29.3	127x114x29	**139**	109	533x210x109	**178**	140.1	686x254x140
3	**34.2**	26.9	127x114x27	**129**	101.2	533x210x101	**190**	149.2	610x305x149

Table 3 Results using GA in Optimization showing the minimised sectional areas, weights and costs obtained

Code	Method	Purlin UB	Rafter UB	Column UB	Weight, kg	Cost (₦)
BS 5950	GA (Optimum) Run 1	**127 x 114 x 27**	**457 x 191 x 98**	**610 x 229 x 140**		
		26.9	98.3	139.9	265.1	97,424.25
		26.9*6 = 161.4	98.3*15.4=1513.82	139.9*7=979.3	**2,654.52**	**975,536.10**
		161.4*255=41157	1513.82*36=54497.52	979.3*36=35254.8	**130,909.32**	**48,109,175.10**
BS 5950	GA (Optimum) Run 2	**127 x 114 x 29**	**533 x 210 x 109**	**686 x 254 x 140**		
		29.3	109	140.1	278.4	102,312.00
		29.3*6=175.8	109*15.4=1678.6	140.1*7=980.7	**2835.1**	**1,041,899.25**
		175.8*255=44829	1678.6*36=60429.6	980.7*36=35305.2	**140563.8**	**51,657,196.50**
BS 5950	GA (Optimum) Run 3	**127 x 114 x 27**	**533 x 210 x 101**	**610 x 305 x 149**		
		26.9	101.2	149.2	277.3	101,907.75
		26.9*6=161.4	101.2*15.4=1558.48	149.2*7=1044.4	**2764.28**	**1,015,872.90**
		161.4*255=41157	1558.48*36=56105.28	1044.4*18=37598.4	**134860.68**	**49,561,299.90**

Table 4 Results using the empirical method showing the cross-sectional area, weight and cost obtained

BS 5950	Empirical	**127 x 114 x 29**	**533 × 210 × 122**	**610 × 229 ×140**	Weight, kg	Cost (₦)
		29.3	122	139.9	291.2	107,016.00
		29.3*6=175.8	122*15.4=1878.8	139.9*7=979.3	**3033.9**	**1,114,958.25**
		175.8*255=44829	1878.8*36=67636.8	979.3*36=35254.8	**147720.6**	**54,287,320.50**

DISCUSSIONS

The results confirm that the developed GA-based program can effectively design and optimise steel portal frames. However, variations in results may occur due to the influence of initial population and elite settings. The application of GA significantly reduced member sizes, yielding 4–11.5% cost savings compared to the empirical method. The optimisation model was further validated against published studies, showing close agreement with previous results despite minor differences in geometry and weight calculation methods. Table 5 shows a comparison with previous literature results.

Table 5a Comparison with Previous Works: Works by other authors

Researchers	**Column sections UB**	**Rafter sections UB**	**Depth of haunch (m)**	**Length of haunch (m)**	**Weight, kg**
Saka (2003)	610 x 229 x 101	356 x 127 x 33	1.50	0.42	**2260.0**
DO-DGA, BS5950	533 x 210 x 82	457 x 152 x 60	1.75	0.47	2138.0
DO-DGA, EC3	533 x 210 x 82	457 x 152 x 52	1.95	0.85	2028.2
Issa and Mohammed (2010)	457× 152 × 52	406 × 140 × 46	0.11	2.45	-
Phan et al. (2013)	457 × 152 ×52	356 × 127 × 33	0.49	3.60	-
Ross Mckinstray et al.(2014)	457 × 152 × 52	356 × 127 × 33	n/a	5.13	-

Table 5b Comparison with Previous Works: Present Work

a) Present Study (GA)	610 x 229 x 140	457 x 191 x 98	n/a	n/a	**2493.12**
b) Present Study (GA)	686 x 254 x 140	533x210 x 109	n/a	n/a	**2659.3**
Phan et al. (2013)	610 × 229 ×113	533 × 210 × 82	0.515	4.20	-
Ross Mckinstray et al.(2014)	610 × 229 ×113	533 × 210 × 82	n/a	4.99	-
c) Present Study (GA)	610 x 305 x 149	533 x 210 x 101	n/a	n/a	**2602.88**

It is worth noting that many comparative studies in the literature focused on spans of 20–25 m, while this study extends to spans of up to 30 m, representing a larger scale (Silva & Pimentel, 2022). Consequently, some variation in results is expected for the 30 m span case. However, when comparing only the 20–25 m span models studied here against those prior works, the optimum section sizes are broadly similar, confirming consistency of the method. The detailed results also reveal that in optimum designs the column's plastic section modulus is about 50 % greater than that of the rafter, the rafter depth approximates span/55, the rafters are 30–40 % lighter than the columns, and the purlin depth is around 0.25 of rafter depth. Additionally, while no two GA runs were identical due to their stochastic nature, all results fell within the same bounded range.

Comparison of Empirical Results and Genetic Algorithm Results

Table 3 showed the result obtained in using GA in the optimisation, and Table 6. illustrates what was obtained using the empirical method.

Table 6: Mass and Cost Calculation of the Frame using Empirical Results

	Column	Rafter	Purlin
Section Designation	610 x 229 x 140	510 x 210 x 122	127 x 114 x 29
Masses (kg/m)	139.9	122	29.3
Each length: Mass(kg)	139.9x7=979.3	122x15.4=1,878.8	29.3x6=175.8
Full Structure: Mass(kg)	979.3 x 36 = 35,254.8	1,878.8 x 36 = 67,636.8	175.8 x 255 = 44,829
Total mass for each length(kg) = 979.3 + 1,878.8 + 175.8 = **3,033.9kg**			
Total mass for full structure(kg) = 35,254.8+ 67,636.8 +44,829 = **147,720.6kg**			

N/B: The columns, rafters and purlins are assumed to have a uniform density

Cost of Steel

Material: I Section = ₦227,5000/ton

Erection & Installation = ₦105,000 - ₦210,000/ton

Assuming Erection & Installation = ₦140,000/ton

Then for Material, Erection & Installation = ₦227,500/ton + ₦140,000

= ₦367,500/ton

= ₦367.5/kg

For total mass for each length,

Total Cost (₦) = 3,033.9 x 367.5 = ₦1,114,958.25

For total mass for full structure,

Total Cost (₦) =147,720.6x367.5 = ₦54,287,320.50

Comparing GA results with empirical results indicated a 4-13% savings in cost using GA. Also, with GA there is an improvement in both weight and cost minimization.

CONCLUSION

This study successfully developed and applied a MATLAB-based Genetic Algorithm (GA) program for the design and optimisation of steel portal frames. The results demonstrate that the algorithm reliably identifies optimal cross-sectional dimensions that minimise frame weight and total cost while maintaining structural adequacy. Compared with the empirical design method, the GA approach achieved 4–13 % cost savings, confirming its effectiveness in generating more economical and material-efficient designs.

The optimisation procedure also established clear proportional relationships among frame components — the column's plastic modulus was approximately 50 % greater than that of the rafter, rafter depth averaged about span/55, and purlin depth was roughly 0.25 of rafter depth. These relationships align with typical portal frame behaviour and validate the robustness of the developed model (Silva & Pimentel, 2022; Salama et al., 2023).

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