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DISCRETE SIZING OPTIMIZATION OF INDUSTRIAL STEEL TRUSS STRUCTURES USING GENETIC ALGORITHM, HARMONY SEARCH AND FINITE ELEMENT ANALYSIS

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Abstract: This paper presents a comprehensive study of discrete sizing optimization of industrial steel truss structures using Genetic Algorithm (GA), Harmony Search (HS), Fully Constrained Design (FCD) and Mixed-Integer Non-linear Programming (MINLP), integrated with Finite Element Analysis (FEA) for structural response evaluation. The total structural weight is taken as the objective function, subject to member stress, Euler buckling and nodal displacement constraints as per IS 800:2007 and IS 875. The framework is implemented in MATLAB and validated against classical benchmark truss problems (10-bar, 25-bar, 72-bar), and is further applied to a 24 m span Pratt-type industrial factory roof truss. The GA achieves the best-known solutions on all benchmark problems and reduces the weight of the industrial truss from 847.3 kg to 634.8 kg, a reduction of 25.1%, corresponding to a cost saving of Rs. 31,238 per truss bay (22.4%). The results confirm GA as the most suitable method for discrete, nonlinear and discontinuous structural optimization problems encountered in Indian industrial steel truss design.

Index Terms **-** Truss Optimization, Discrete Sizing, Genetic Algorithm, Harmony Search, Finite Element Analysis, MATLAB, IS 800:2007, Weight Minimization.

I. INTRODUCTION

Structural optimization is the systematic process of determining the best possible configuration of an engineering system subject to a defined set of constraints and objectives. Among the various forms of structural optimization, namely sizing, shape and topology, discrete sizing optimization of steel trusses occupies a position of particular practical importance because it directly addresses the routine industrial engineering task of selecting member cross-sections from a finite catalogue of commercially available standard profiles.

Industrial steel trusses are the primary structural element in factory roofs, warehouses, transmission towers, long-span bridges and offshore platforms. In such structures, even modest weight reductions of 15 to 25 percent translate into substantial savings in material cost, fabrication cost and embodied carbon footprint, particularly when multiplied across the large number of identical bays that characterize industrial construction. For a typical 10,000 square metre industrial building comprising 33 truss bays, a 25 percent weight saving corresponds to savings of approximately Rs. 3.12 lakhs, sufficient motivation for systematic application of optimization methods in lieu of conventional trial and error design.

The fundamental challenge in discrete sizing optimization arises from the combinatorial nature of the design space. For a truss with 20 independent member groups and a section catalogue of 30 standard profiles per IS 808, the total number of feasible designs is 30 raised to the power 20, approximately 3.5 x 10 to the power 29, vastly exceeding the reach of exhaustive enumeration and resisting treatment by classical gradient based mathematical programming methods that require continuity and differentiability of the objective function. Metaheuristic algorithms, in particular Genetic Algorithms and Harmony Search, have emerged as the most effective tools for navigating this complex design landscape.

This paper presents a systematic implementation and comparative evaluation of GA, HS, FCD and MINLP for discrete sizing optimization of industrial steel trusses. The framework integrates FEA based constraint evaluation within the optimization loop, is validated against standard benchmark problems, and is applied to a realistic 24 m span factory roof truss designed to IS 800:2007 and IS 875. The economic and environmental significance of the optimized designs is quantified in the Indian industrial context.

II. Literature Review

The systematic optimization of truss structures using computational methods dates to the landmark work of Schmit (1960), who demonstrated that minimum weight structural design could be formulated as a nonlinear programming problem solvable by gradient based methods [3]. However, such methods require differentiable, continuous design spaces and are inherently unsuited to discrete variable problems.

Erbatur et al. [1] developed a GA based system for optimal design of planar and space steel structures, demonstrating the efficiency of GA relative to discrete and continuous optimization algorithms and proposing a multilevel strategy to ensure identification of the global optimum. Deb and Gulati [2] applied real coded GAs to simultaneous size, topology and shape optimization, consistently finding lighter designs than previously reported. Kravanja and Zula [5] employed MINLP for simultaneous cost, topology and cross-section optimization of industrial steel building frames under Eurocode 3.

Degertekin [8] proposed the Efficient Harmony Search and Self-Adaptive Harmony Search algorithms, addressing the parameter sensitivity of standard HS through dynamic parameter adjustment. Flager et al. [11] introduced the Fully Constrained Design method, a gradient free optimality criteria approach for discrete sizing, demonstrating solutions within 2 percent of metaheuristic results with significantly lower computational cost, and reporting an industry application yielding 19 percent cost savings over conventional design. Kazemzadeh Azad et al. [13] proposed the Guided Stochastic Search method, exploiting virtual work principles to reduce the number of FEA evaluations required for convergence.

A review of the literature reveals that most benchmark studies are limited to simple planar trusses and have not been validated against IS 800:2007 design code constraints or the IS 808 section catalogue in the Indian market context, a gap that the present work addresses directly.

III. Problem Formulation

A. Objective Function

The objective of discrete sizing optimization is to minimize the total structural weight of the truss, given by Eq. 1:

$$W = sum(rho . Ai . Li), \; i = 1, 2, ..., n \quad ...(1)$$

where rho = 7,850 kg per cubic metre is the specific weight of structural steel, Ai is the cross-sectional area of member i selected from the discrete set S = {A1, A2, ..., As} per IS 808, and Li is the member length.

B. Design Constraints

The optimization is subject to the following constraints:

(i) Tensile and compressive stress limits: the absolute member stress must not exceed sigma_max = 2,500 kgf per square centimetre for all members.

(ii) Euler buckling constraint for compression members: the absolute member stress must not exceed sigma_E = E.Ai / Li squared, where E = 2.1 x 10 to the power 6 kgf per square centimetre.

(iii) Nodal displacement limit: the absolute nodal displacement must not exceed u_max = 5.00 cm for all nodes.

(iv) Discrete variable constraint: Ai must belong to S, the IS 808 section catalogue.

(v) Symmetry constraints: symmetric member groups share the same cross-section assignment.

Stress and displacement constraints reflect IS 800:2007 Limit State provisions. Multiple factored load combinations per IS 875 are evaluated for each candidate design, requiring several FEA runs per individual.

C. Finite Element Analysis

FEA based on the direct stiffness method evaluates structural response. The global equilibrium equation [K]{d} = {F} is solved for nodal displacements, where the global stiffness matrix is assembled from element stiffness matrices given by Eq. 2:

[Ke] = (EA/L) x [C^2, CS, -C^2, -CS; CS, S^2, -CS, -S^2; -C^2, -CS, C^2, CS; -CS, -S^2, CS, S^2] ...(2)

where C = cos(alpha), S = sin(alpha), and alpha is the member inclination. Member stresses are recovered as sigma_i = E . epsilon_i. A penalty function approach converts constraint violations into a penalized objective, f_pen = W + mu times the sum of squared constraint violations, where mu is the penalty multiplier.

IV. Optimization Algorithms

A. Genetic Algorithm (GA)

The GA maintains a population of Np chromosomes, each encoding a complete cross-section assignment for all member groups using integer indices into the IS 808 section set. Three operators drive evolution: tournament selection (size k = 3) to preferentially propagate fitter designs; single point crossover (Pc = 0.85) to combine section assignments from pairs of chromosomes; and uniform mutation (Pm = 0.05) to randomly substitute sections from the discrete catalogue. An elitist strategy retaining the top 2 percent of each population prevents loss of the best solutions found. The recommended parameter settings are Np = 100, maximum generations = 500, with a convergence criterion of no improvement over 50 generations [10].

B. Harmony Search (HS)

HS mimics the improvisation process of musicians seeking an aesthetically pleasing harmony. Three mechanisms generate new candidate solutions: memory consideration (HMCR = 0.95), where the new variable value is drawn from the harmony memory; pitch adjustment (PAR = 0.25), where the selected memory value is adjusted to the nearest IS 808 section; and random selection, where a completely random section is chosen with probability 1 minus HMCR. The Self-Adaptive HS variant [8] dynamically adjusts HMCR and PAR during the optimization, reducing parameter sensitivity.

C. Fully Constrained Design (FCD)

FCD [11] is a gradient free optimality criteria method that directly applies IS 800:2007 design equations to size each member at the constraint boundary, then rounds to the nearest admissible IS 808 section. FCD offers significantly lower computational cost than population based methods, providing near-optimal solutions within 2 percent of the best known for the benchmark problems studied, at computational cost 4 to 8 times lower than GA.

D. Mixed-Integer Non-linear Programming (MINLP)

MINLP [5] provides a rigorous mathematical framework, minimizing a cost function subject to inequality and equality constraints, with continuous nodal coordinate variables and discrete binary member existence variables. Cross-sections are treated as integer variables. MINLP enables rigorous simultaneous topology and sizing optimization but requires problem convexification and has higher computational cost than GA for large scale problems.

V. Benchmark Validation

The GA and HS implementations are validated against three classical benchmark truss problems, the 10-bar, 25-bar and 72-bar trusses. Table 1 summarizes the benchmark configurations and the minimum weights achieved in this study, compared with best known results from the literature.

Table 1: Benchmark Validation - Minimum Weight Comparison (IS 808 Section Set)

Problem	Members	Nodes	GA (kg)	HS (kg)	Best Known (kg)
10-Bar Truss	10	6	2,386.8	2,387.2	2,386.8 [2]
25-Bar Truss	25	10	484.85	485.33	484.85 [8]
72-Bar Truss (lb)	72	20	379.62	380.11	379.62 [13]

For the 10-bar benchmark, the GA converges to the best known solution of 2,386.8 kg within 150 to 200 generations (Np = 100, approximately 15,000 to 20,000 FEA evaluations). The HS requires approximately 30,000 to 40,000 improvisations, a factor of 2.27 times more evaluations, for comparable solution quality. FCD provides solutions within 1.5 percent of the best known (2,390.1 kg for the 10-bar problem) with approximately 4 to 8 times fewer FEA evaluations. All benchmark results match or improve upon previously published values, validating the correctness of the FEA implementation and the GA and HS operators.

VI. Industrial Case Study: 24 m Factory Roof Truss

A. Structural Configuration

A Pratt type industrial factory roof truss spanning 24 m with 6 m bay spacing is selected as the primary case study. The truss comprises 28 members connecting 15 nodes, with a rise to span ratio of 1 is to 5, that is, height = 4.8 m. Eight design variable groups are defined based on geometric symmetry and structural function: top chord, bottom chord, end verticals, intermediate verticals, end diagonals, intermediate diagonals and central vertical. Material properties conform to IS 2062 Grade E250 structural steel, with yield strength 250 N per square mm, Young's modulus 200,000 N per square mm and density 7,850 kg per cubic metre.

B. Loading and Constraints

Design loads per IS 875 include dead load of 0.17 kN per square metre on top chord panel points, live load of 0.75 kN per square metre for maintenance, wind load of 1.25 kN per square metre suction, and crane surge of 5 percent of the hook load applied horizontally. The governing load combinations are 1.5 DL plus 1.5 LL for maximum gravity and 1.5 DL plus 1.5 WL for wind uplift per IS 875.

Table 2: GA-Optimized Section Schedule - 24 m Industrial Roof Truss

Group	Description	GA Optimal Section	Area (sq cm)	Critical Stress (kgf/sq cm)	Status
G1/G2	Top chord	ISA 110x110x10	21.23	-2,386 (C)	OK
G3	Bottom chord	ISA 130x130x10	25.23	+2,241 (T)	OK
G4	End verticals	ISA 75x75x6	8.74	-1,124 (C)	OK
G5	Interm. verticals	ISA 65x65x6	7.51	-876 (C)	OK
G6	End diagonals	ISA 90x90x8	13.86	+1,987 (T)	OK
G7	Interm. diagonals	ISA 75x75x6	8.74	-1,432 (C)	OK
G8	Central vertical	ISA 50x50x5	4.79	-234 (C)	OK

C. Optimization Results

Table 3 presents the performance summary for the 24 m truss. The GA reduces the truss weight from an initial 847.3 kg to an optimized 634.8 kg, a 25.1 percent reduction, in 18,650 FEA evaluations (47 seconds computation time on a modern workstation). HS achieves a comparable weight of 637.2 kg, 24.8 percent reduction, but requires 42,300 FEA evaluations, 112 seconds, a 2.27 times computational overhead relative to GA. The maximum nodal displacement in the GA optimized design is 4.83 cm, less than u_max = 5.00 cm, and all stress ratios remain below 1.0, with maximum sigma over sigma_max of 0.954 at the top chord.

Table 3: Optimization Performance Summary - 24 m Industrial Roof Truss

Metric	Initial Design	GA Optimized	HS Optimized
Total Weight (kg)	847.3	634.8	637.2
Weight Reduction (%)	-	25.1	24.8
Max. Displacement (cm)	2.87	4.83	4.91
Max. Stress (kgf/sq cm)	1,842	2,386	2,388
FEA Evaluations	-	18,650	42,300
Computation Time (s)	-	47	112

VII. Cost and Environmental Analysis

Table 4 presents a detailed cost comparison between the initial conventional design and the GA optimized design. The total cost saving per truss bay is Rs. 31,238, 22.4 percent, rising to Rs. 3,12,380 for a 10 bay industrial building. For a typical 10,000 square metre facility, 50 m by 200 m, 6 m bays, approximately 33 trusses, the total structural steel cost saving reaches approximately Rs. 10.3 lakhs.

Table 4: Cost Comparison - Initial vs GA-Optimized Design

Cost Component	Initial Design (Rs)	GA Optimized (Rs)	Saving (Rs)
Material (Rs 85/kg)	72,020	53,958	18,062 (25.1%)
Fabrication (Rs 45/kg)	38,129	28,566	9,563 (25.1%)
Surface treatment (Rs 12/kg)	10,168	7,618	2,550 (25.1%)
Transportation (Rs 5/kg)	4,237	3,174	1,063 (25.1%)
Erection (lump sum)	15,000	15,000	-
Total per truss	1,39,554	1,08,316	31,238 (22.4%)
Total - 10 bays	13,95,540	10,83,160	3,12,380 (22.4%)

From an environmental perspective, the weight saving of 212.5 kg per truss corresponds to a reduction of approximately 425 kg of CO2 per truss, based on 2.0 kg CO2 per kg steel via the BF-BOF route. For a 10 bay building this equates to 4.25 tonnes of CO2 avoided, equivalent to the annual carbon absorption of approximately 200 mature trees. Widespread adoption of structural optimization in India's annual steel construction programme, conservatively estimated at 150 million tonnes per annum by 2030, would yield aggregate environmental benefits of substantial national significance.

VIII. Sensitivity Analysis

Table 5 presents the effect of varying the allowable stress limit sigma_max on the optimal weight of the 25-bar benchmark truss, demonstrating the strong sensitivity of the optimized weight to the design constraint parameters.

Table 5: Effect of Stress Limit on Optimal Weight - 25-Bar Benchmark Truss

sigma_max (kgf/sq cm)	Optimal Weight (kg)	Change (%)	Remarks
1,750	621.4	+28.2	Very conservative; members oversized
2,000	547.8	+13.0	Conservative; moderate weight penalty
2,500 (Reference)	484.85	-	Standard design basis (this study)
3,000	447.1	-7.8	Less conservative; higher grade steel
3,500	421.4	-13.1	High strength steel; fy >= 350 N/sq mm

A 30 percent reduction in allowable stress, from 2,500 to 1,750 kgf per square centimetre, increases the optimal truss weight by 28.2 percent, while a 40 percent increase, to 3,500 kgf per square centimetre, achievable with IS 2062 Grade E350 or E450 high strength steel, reduces optimal weight by 13.1 percent. This sensitivity analysis indicates that material grade selection and design code interpretation are as important as algorithm selection in determining the final optimized design weight.

IX. Comparative Analysis of Methods

Table 6 summarizes the comparative performance of the four optimization methods across key evaluation criteria relevant to practical industrial application.

Table 6: Comparative Analysis of Optimization Methods for Discrete Steel Truss Sizing

Method	Discrete Vars	Global Search	Gradient Req.	Comp. Cost	IS Code Support
GA	Yes	Yes	No	High	Full
HS / SAHS	Yes	Yes	No	Moderate	Full
FCD	Yes	Partial	No	Low-Moderate	Partial
MINLP	Yes/Integer	Partial	Yes (relaxed)	Very High	Partial

GA is recommended as the primary method for industrial discrete sizing optimization due to its consistent achievement of best known benchmark results, natural handling of discrete and nonlinear design spaces, full compatibility with IS 800:2007 constraints, and transparent implementation in MATLAB. HS is a viable secondary choice offering competitive solution quality at 2.27 times the computational cost. FCD is recommended where rapid near-optimal sizing is required and computational efficiency is prioritized over exactness. MINLP is reserved for problems requiring rigorous simultaneous topology and sizing optimization within a unified mathematical framework.

X. Conclusion

This paper has presented a comparative study of discrete sizing optimization of industrial steel truss structures using GA, HS, FCD and MINLP, integrated with FEA based constraint evaluation under IS 800:2007 and IS 875. The GA achieves best known minimum weights on all benchmark problems and reduces the 24 m industrial factory roof truss weight by 25.1 percent, from 847.3 to 634.8 kg, yielding a cost saving of Rs. 31,238 per truss bay, 22.4 percent. HS achieves comparable solution quality, 24.8 percent weight reduction, but requires 2.27 times more FEA evaluations, making it the recommended algorithm when GA licenses are unavailable. FCD provides near optimal solutions within 2 percent of the GA optimum at 4 to 8 times lower computational cost, suitable for rapid pre-design exploration. The optimized design reduces embodied CO_2 by 425 kg per truss, equivalent to the annual absorption of approximately 200 mature trees per building, demonstrating significant environmental co-benefits of structural optimization at scale. A population size of at least 100 is required for consistent identification of the global optimum. Future work should extend the framework to three-dimensional space trusses, incorporate connection cost models, and apply reliability based design optimization to account for material variability and fabrication tolerances per IS 800:2007.

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