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# A COMPREHENSIVE REVIEW ON GENETIC ALGORITHM-BASED OPTIMIZATION OF STEEL TRUSS STRUCTURES FOR WEIGHT REDUCTION AND STRUCTURAL EFFICIENCY

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## ABSTRACT

The steel truss structure is a typical engineering structure since it is extremely robust relative to its weight and its structure. Nevertheless, there is still a considerable challenge in trying to optimize these structures to ensure minimum weight, safety and performance. Conventional optimization methods may be ineffective in dealing with nonlinear and multiple constraints design spaces. The artificial algorithms based on the concept of natural selection and evolution that have become a powerful tool to resolve such optimization problems are called Genetic Algorithms (GAs). This review paper will discuss in detail the GA-based optimization solution to steel truss structures. It talks about techniques, encoding, constraint management, mixed methods and newer techniques. Challenges, comparative studies, future research directions are also pointed out in the paper.

**Keywords:** Genetic Algorithm, Steel Truss Optimization, Structural Efficiency, Weight Minimization, Metaheuristic Techniques, Evolutionary Computation

## INTRODUCTION

The steel trusses structures form an essential part of the current civil and structural engineering systems and have an important role in the construction of bridges, transmission towers, industrial sheds, space frames and long span roof structures. Their most remarkable usage is mostly due to their high strength-to-weight ratio, structural stability, manufacturing simplicity and economic cost-effectiveness Kaveh and Mahdavi (2019). Trusses also reduce the number of bending moments in members by transferring the loads efficiently in the axial force of the members thus allowing less material to be used without the sacrifice of structural integrity.

The basic aim of designing the steel truss is to ensure optimum structural performance of minimum material consumption which in turn leads to cost minimization, better sustainability and resource efficiency Alkhraisat et al. (2023). Reducing structural weight in the present era of sustainable engineering practices is not only a cost-reducing factor in the construction process but also a less harmful factor in terms of the environment since less material is used and less carbon is produced during the process of steel manufacturing.

Conventionally, the design of trusses has been conducted on a trial-and-error basis or classical optimization processes like gradient-based methods Ho-Huu et al. (2018). These traditional techniques are usually time consuming and inefficient as they rely on the experience and intuition of the designer. Moreover, gradient-based optimization models require that the objective function is a continuous and differentiable function and these limits their applicability to complex structural problems with discrete variables,

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nonlinear relationships and multi-constrained problems. Therefore, these methods will tend to be local optima and not obtain a global optimum solution Pham (2019).

To address these disadvantages, innovative advanced computational optimization techniques have been suggested, and Genetic Algorithms (GAs) have been the topic of much concern. Genetic Algorithms: Genetic Algorithms are stochastic search and optimization algorithms, which are founded on natural selection and genetics Grzywiński and Selejdak (2019). They are particularly useful to complex engineering problems, since they are able to solve problems with large search space, nonlinear objective and discrete design variables without need to know the gradient information.

## OBJECTIVES OF THE STUDY

The current review article seeks to accomplish the following goals:

1) To critically examine the application of Genetic Algorithms (GA) in optimization of steel truss structures to achieve the least structural weight and higher efficiency.
2) To test various optimization methods, including optimization of size, shape and topology of steel trusses, using the GA based technology.
3) To investigate various encoding techniques and constraint-handling schemes that can be used in Genetic Algorithms to solve complex structural optimization problems.
4) To test the hybrid optimization algorithms that are the combinations of Genetic Algorithms with other optimization algorithms such as Finite Element Analysis (FEA), Particle Swarm Optimization (PSO) and Simulated Annealing (SA) to increase the accuracy of solutions and the convergence rates.

## FUNDAMENTALS OF STEEL TRUSS OPTIMIZATION

One of the most critical aspects of structural engineering is also steel truss optimization since it aims to create an effective balance between performance, safety and economics. It is done by systematically finding the optimal design configuration by changing variables like the size of the member, geometry and connectivity to meet a predetermined set of constraints Mehta et al. (2025). To improve structural behaviour, minimize material usage, and meet design standards, optimization techniques are used.

**Figure 1**

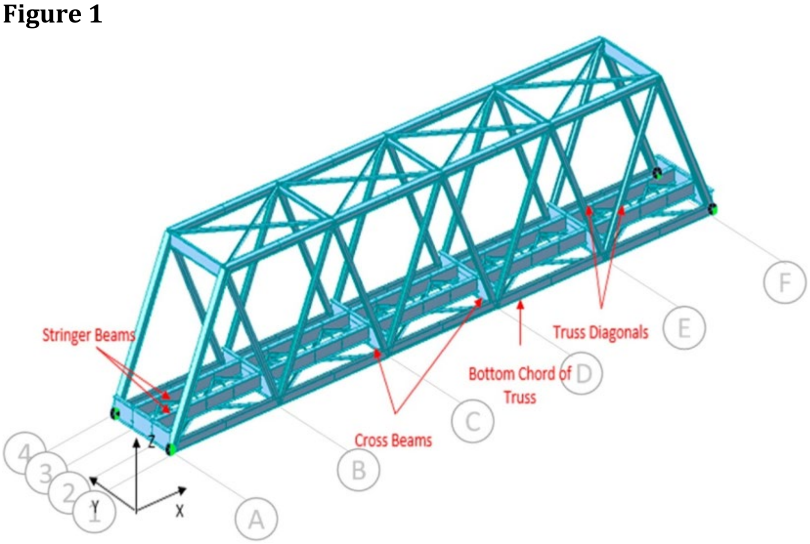


**Figure 1 Components of a Steel Truss Structure (Including Chords, Diagonals, and Beams)**

## OBJECTIVES OF OPTIMIZATION

Optimization of steel trusses aims mostly at enhancing the structural performance at the lowest possible cost in terms of resource use. The following are the summarization of these objectives:

- **Minimization of Structural Weight:** One of the most important goals is to reduce the total weight of the structure. It will result in cost-saving in the material, transportation, and construction as well as help in sustainability through reduced consumption of resources.

- **Maximization of Stiffness and Strength:** Optimized designs have the goal of increasing the load bearing and stiffness of the structure. Greater stiffness will guarantee decreased deflections and enhanced strength that guarantees safety in several loading conditions.
- **Reduction of Material Cost:** Economic benefits are directly proportional to efficient use of materials Li et al. (2021). Optimization aims at utilizing minimum material without affecting structural performance or safety.
- **Compliance with Design Constraints:** The design should meet all the engineering requirements such as stress boundaries, displacement limits and buckling limits to ensure safe and dependable performance under recommended loading conditions.

## DESIGN VARIABLES

The parameters that can be changed in the course of optimization to attain the desired objectives are the design variables. These variables can be commonly classified in the following way in steel truss optimization:

- **Cross-Sectional Areas of members (Size Optimization):** Truss member sizes have a great impact on the weight and strength of the structure. Modifications of cross-sectional areas assist in attaining a good balance between strength and material consumption.
- **Node Positions (Shape Optimization):** The geometry and load distribution in the truss is sensitive to the spatial arrangement of the nodes Akbari and Henteh (2019). Adjusting node positions can result in better structural performance and minimization of stress concentrations.
- **Topology (Connectivity of Members):** Topology optimization finds the optimal way to arrange the members and can be achieved by deciding which elements to include or exclude. This leads to innovative structural forms with enhanced efficiency.

## CONSTRAINTS

Constraints will stipulate the limits within which the optimization process should be carried out. These are necessary to be sure that the final design is safe, functional and can meet the engineering standards.

- **Stress Limits:** Stress in the individual member should not surpass the stress values to be accepted by the material to avoid failure.
- **Displacement Limits:** Structural deflections should not be allowed to be of such magnitude that serviceability or comfort of the user is compromised.
- **Stability Constraints (Buckling):** Compressive forces on members should be inspected to prevent buckling to make the entire structure stable.
- **Code-Based Requirements:** The design should be based on the standard and code of design like Bureau of Indian Standards (IS codes) and American Institute of Steel Construction (AISC) which give the guidelines of safe and reliable design of the structure.

**Table 1**

**Table 1 Key References on Genetic Algorithm-Based Structural Optimization**

| Author(s) & Year | Study Focus | Key Findings | Relevance to Section |
|---|---|---|---|
| Mirnateghi and Mosallam (2021) | Multi-criteria optimization of energy-efficient cementitious sandwich panel systems using Genetic Algorithms | Proved that GA can be used to optimize the structural and energy performance concurrently, producing a better sustainability and cost efficiency. | Supports multi-objective optimization and GA applicability in structural systems (Sections 4 & 6) |
| Chen et al. (2020) | Optimization of steel–concrete hybrid wind turbine towers using improved GA | Enhanced GA increased the rate of convergence and offered the best design solutions with excellent structural performance and less use of materials. | Relevant to hybrid GA approaches and real-world structural optimization (Section 7) |
| Toğan and Daloğlu (2015) | Application of Genetic Algorithms in optimization of 3D truss structures | GA effectiveness in optimization of complex 3D truss systems with less weight and enhanced efficiency has been demonstrated. | Directly supports GA-based truss optimization concepts (Section 4) |

| | | | |
|---|---|---|---|
| Guimarães et al. (2022) | Optimization of concrete-filled steel columns using GA with environmental and cost considerations | Outlined the potential of GA to balance cost, structural performance, and environmental impact by use of multi-objective optimization. | Supports sustainability and cost optimization using GA (Sections 2 & 6) |
| Grzywiński (2020) | Size and shape optimization of truss structures using Jaya algorithm (comparative approach) | Demonstrated that metaheuristic techniques are useful in optimising truss structures, and that they perform competitively with GA-based techniques. | Provides comparative perspective on metaheuristics, supporting GA relevance (Section 7) |

## GENETIC ALGORITHM: OVERVIEW

GAs are a group of evolutionary optimization algorithms that are commonly applied to solve complex engineering optimization problems. The GAs are based on the concepts of natural selection and Darwinian evolution and model the process of survival of the fittest to find the best or the best possible solutions in the large search space Yücel et al. (2024). They have been especially useful in structural optimization, because of their strength and flexibility, in tasks where the space of solutions is nonlinear, discontinuous, and constrained, like the design of steel trusses.

## BASIC CONCEPT

The basic idea behind Genetic Algorithms is to imitate natural evolution. This method involves a pool of potential solutions, referred to as individuals or chromosomes that evolves with each generation. The possible solutions to the optimization problem are each represented as a chromosome, in an appropriate format like binary strings, real numbers or integers.

Three major genetic operators control the process of evolution:

- **Selection:** This operator chooses the fittest of the existing population according to the values of their fitness. Fitter individuals are more likely to be selected to reproduce, whereby better solutions are replicated to another generation.
- **Crossover (Recombination):** Crossover involves the combination of genetic information of two parent chromosomes to give out one or more offspring. The process helps to facilitate the process of the desired traits exchange and improves the search space exploration.
- **Mutation:** Mutation brings randomness in the chromosomes in order to maintain genetic diversity in the population. It can avoid premature convergence and enables the algorithm to search new areas of the solution space.

By successive trial and error in the use of these operators, there is a gradual evolution of the population to optimal or near-optimal solutions.

## GA WORKFLOW

The working procedure of a Genetic Algorithm follows a systematic and iterative process:

- **Initialization of Population:** Randomly generated set of candidate solutions are produced within the search space. This set of population is the starting point of the optimization process.
- **Fitness Evaluation:** Each candidate solution is measured by a fitness function which is a measure of how well the solution meets the optimization objectives and constraints. When it comes to optimization of steel truss, the overall goal is usually to minimize the weight of the structure with all the design requirements, including stress, displacement, and stability limits, being met. The fitness is given by the expression:

$$F(x) = W(x) + \lambda \sum_{i=1}^{m} g_i\,(x)$$

represents the weight of the structure, $g_i(x)$ represents the functions of constraint violation, k is the quantity of constraints, and $\lambda$ is the coefficient of penalty. This formulation punishes solutions that are infeasible and thus the Genetic Algorithm is directed to work towards solutions that are feasible and optimal designs.

- **Selection of Parents:** Roulette wheel selection, tournament selection or rank selection are some of the methods that can be used to select individuals to reproduce depending on the fitness value.
- **Crossover and Mutation:** The parents of selected parents are exposed to crossover and mutation to create new offspring which introduce variation and enhances the quality of solutions.

- **Generation of New Population:** The children displace part or entire members of the existing population, creating a new generation.
- **Criterion Based Termination:** It continues until an algorithmic objective is achieved, such as the greatest number of generations, the sought fitness or convergence.

**Figure 2**

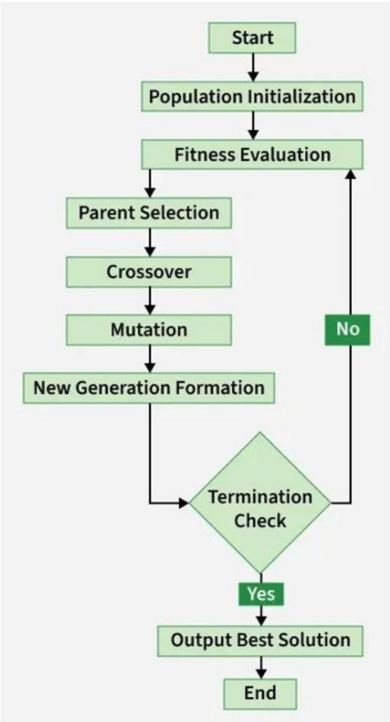


**Figure 2 Flowchart of Genetic Algorithm Process**

## ADVANTAGES OF GENETIC ALGORITHMS

Genetic Algorithms have a number of strengths that render them very applicable to structural optimization problems Carbas and Artar (2022):

- **Global Search Capability:** GAs investigations vary across the search space, which decreases the likelihood of local optima.
- **No Gradient Information Requirement:** Compared to the traditional optimization methods, GAs do not require derivative information, and as a result, can be extended to non-differentiable and complex problems.
- **Appropriateness in Discrete and Nonlinear Problems:** GAs can be applied in solving problems of discrete variables, nonlinear relationships, and numerous constraints, common in truss optimization.
- **Flexibility in Constraint Handling:** Penalty functions, repair methods, or special operators may be used to incorporate constraints and enable GAs to effectively solve constrained optimization problems.

## APPLICATION OF GENETIC ALGORITHMS IN STEEL TRUSS OPTIMIZATION

GAs have also found wide applications in optimization of steel truss structures because of their ability to solve complex, multi-variable and nonlinear design problems. In structural engineering, optimization using GA is mainly divided into size, shape, and topology optimization Serpik et al. (2017).

## SIZE OPTIMIZATION

The most popular application of Genetic Algorithms in steel truss design is size optimization, which is frequently applied. It is aimed at defining the optimum cross-sectional areas of truss members and does not compromise structural performance and safety.

In this method, the design variables are the cross-sectional areas of a member, and may be discrete (the standard steel sections) or continuous variables. This is usually aimed at reducing the total structural weight but must meet certain constraints like the stress, displacements, and buckling requirements.

Genetic Algorithms have found application especially in size optimization because it can:

- Handle both discrete and continuous design variables efficiently
- Explore a large design space without requiring gradient information
- Achieve significant reductions in structural weight compared to conventional methods

Many experiments have shown that size optimization using GA can result in a significant reduction in material usage, without degrading structural performance or sometimes improving it.

**Figure 3**

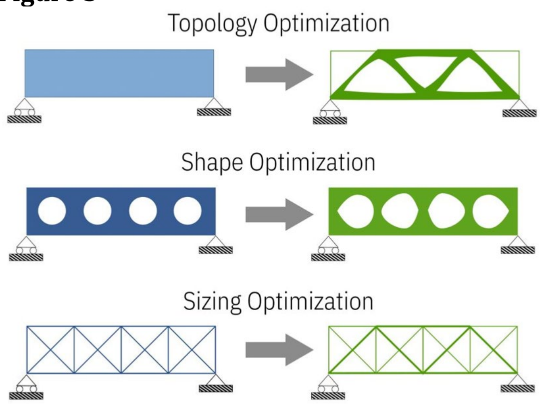


**Figure 3 Types of Structural Optimization: Size, Shape, and Topology Optimization**

## SHAPE OPTIMIZATION

Shape optimization consists of altering the spatial layout of the truss by changing the coordinates of its nodes. The aim is to enhance the structural reaction to the imposed loads by attaining a more effective geometry.

Genetic Algorithms in this form of optimization explore various geometric layouts and determine the most effective layout between nodes. The structure can be modified by changing the position of the nodes in order to redistribute the internal forces and result into an improved performance Es-Haghi et al. (2020).

The main advantages of shape optimization using GA are:

- Enhanced load distribution across members
- Reduction in stress concentrations
- Improved structural stiffness and stability

The optimization of shape is especially applicable in long-span structures where geometry is critical in the performance.

## TOPOLOGY OPTIMIZATION

Topology optimization is concerned with how to connect the truss members to ensure the final structure is the best possible, i.e. which truss members need to exist and which ones need to be eliminated Saravanan et al. (2022). It is a more intricate type of optimization since it presupposes some changes in the structural layout.

In topology optimization based on GA, binary variables are frequently employed, to indicate the presence or absence of members Sun et al. (2022). The algorithm mutates various structural arrangements to determine the most efficient structure.

Topology optimization has the following advantages:

- Elimination of redundant or inefficient members
- Reduction in overall structural weight
- Generation of innovative and non-intuitive structural designs

This approach enables engineers to develop highly efficient truss systems that may not be easily achievable through traditional design methods Sistla and Rama (2021).

## ENCODING TECHNIQUES IN GA

Encoding is a core concept to Genetic Algorithms (GAs) because it describes how design variables are encoded into chromosomes, which directly affects the performance, precision and convergence of the optimization Mroginski et al. (2016). The encoding scheme is a determiner of the efficiency of exploration of the search space and the ability to apply genetic operators, including selection, crossover, and mutation. Binary encoding that encodes variables as a series of binary numbers (0s and 1s) is one of the oldest and most popular methods. It is especially well adapted to discrete optimization problems, like choosing standard member sizes or deciding whether or not to include truss elements in topology optimization Farahmand-Tabar and Ashtari (2020). Its simplicity and ease of implementation due to its simplicity, and its ability to be compatible with classical GA operations although typically requires longer length chromosomes and may not be as precise with continuous variables.

In order to circumvent these shortcomings, it is common practice in the modern world to use real-valued (floating-point) encoding Brütting et al. (2019). The design variables in this approach are defined directly in real numbers and this can more easily and efficiently represent continuous variables such as the cross-sectional areas and the nodal coordinates. Encoding in real values can also simplify computational complexity and increase speed of convergence due to the absence of binary-to-decimal conversion, and the ability to perform search operations in the solution space more smoothly Dolwana (2019).

In real world structural optimization problems, especially in the design of steel trusses, discrete and continuous variables may coexist. In this case, mixed encoding is a dynamic and efficient solution; binary and real-valued representations on the same chromosome. An example is that topology (existence of members) is encodable using binary encoding and geometric and size variables can be encodable using real values. The hybrid representation is optimizable in size, form and topology, which leads to more realistic and efficient design solutions.

## CONSTRAINT HANDLING TECHNIQUES

Constraint management in optimization of steel truss structures with the application of GAs is one of the most important issues of ensuring that the solutions found are both optimal and feasible and safe Jayaram (2022). The nature of the structural optimization problems is such that it is marked by a number of constraints such as stress limits, displacement constraints and stability conditions.

## PENALTY FUNCTION METHOD

One of the most popular methods of dealing with constraints in Genetic Algorithms is the penalty function method. The penalty term is incorporated into the objective function in this approach each time a solution violates a constraint(s). This is a good way of converting a constrained optimization problem to an unconstrained one since it discourages infeasible solutions Nouri and Ashtari (2015).

The new fitness function can be mathematically written as:

$$F(x) = W(x) + \lambda \sum_{i=1}^{m} \max\,(0, g_i(x))$$

where $W(x)$is the objective function (e.g., structural weight), $g_i(x)$represents the constraint violation functions, $m$is the number of constraints, and $\lambda$is the penalty coefficient. The term $\max\,(0, g_i(x))$ensures that only violated constraints contribute to the penalty.

**Advantages:**

- Simple and easy to implement
- Compatible with standard GA operators
- Effective for a wide range of structural problems

**Limitations:**

- Requires careful tuning of penalty parameters
- Excessive penalties may restrict exploration, while low penalties may allow infeasible solutions

## REPAIR METHODS

Repair techniques strive to transform infeasible solutions into feasible ones through adjusting their design variables Saleem (2018). This method is more proactive in enforcing feasibility, rather than penalizing constraint violations, through the active adjustment of the solution.

For example:

- If a member exceeds stress limits, its cross-sectional area may be increased
- If displacement constraints are violated, nodal positions or member sizes may be modified

Repair algorithms are typically applied after genetic operations such as crossover and mutation to ensure that all individuals in the population satisfy the constraints.

**Advantages:**

- Ensures feasibility of solutions
- Improves convergence toward valid designs
- Reduces dependency on penalty parameters

**Limitations:**

- May increase computational complexity
- Requires problem-specific repair strategies

## MULTI-OBJECTIVE OPTIMIZATION

In most real world structural optimization tasks, several conflicting goals need to be addressed at the same time, e.g. a minimization of weight and maximization of strength and a minimization of cost. Multi-objective optimization offers a natural methodology to deal with such problems and constraints Saraskanroud and Babaei (2023).

In GA-based multi-objective optimization, the concept of Pareto optimality is used. A set of non-dominated solutions (Pareto front) is produced instead of a single best solution, in which no single solution is best on all objectives Oluwafemi (2018).

For example:

- One solution may have minimum weight but higher displacement
- Another may have slightly higher weight but better structural performance

This approach allows designers to choose the most suitable solution based on practical requirements Kaveh and Zakian (2018).

**Advantages:**

- Balances conflicting objectives effectively
- Provides multiple optimal design alternatives
- Eliminates the need for predefined weighting factors

**Limitations:**

- Increased computational effort
- Complexity in decision-making from Pareto solutions

## CONCLUSION

Genetic Algorithms have also turned out to be very effective in optimization of steel trusses in an attempt to get the lowest weight but at the same time structural efficiency and performance. They are more appropriate than traditional optimization techniques as they are able to solve complex, nonlinear, and multi-objective problems. The combination of the GAs with other methods like FEA and hybrid methods like PSO and SA increases the accuracy and convergence of the solution even more. Nonetheless, there are still difficulties like the large computational cost, parameter optimization, and earlier convergence. With ongoing advancements and the integration of emerging technologies like artificial intelligence and real-time monitoring systems, GA-based optimization is expected to play an increasingly important role in developing efficient and sustainable structural designs.

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