STRATEGIES, TECHNIQUES, APPLICATIONS AND RESOURCES

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- Dr. Arceloni Neusa Volpato
- Dr. B. Balaji
- Dr. S. Karthikeyan
- Dr. Divya R. Panjwani

Editors

PREFACE

The world is facing unprecedented environmental challenges that are affecting the quality of life of people, ecosystems and economies. The complexity and interdependence of myriad issues require a multidisciplinary approach that brings together expertise from different fields of knowledge (engineering, technology, sciences, arts, humanities, commerce and management). This edited book aims to contribute to this effort by bringing together a collection of articles that explore strategies, techniques, applications and resources from different perspectives.

Strategies are essential because they provide structure, direction, and purpose to endeavors, increasing the likelihood of success and enabling efficient and effective use of resources. They are crucial for adapting to changing circumstances and maintaining a competitive advantage in various contexts.

Techniques are valuable tools that provide structured and efficient ways to perform tasks, solve problems, and achieve goals across diverse fields. They contribute to productivity, quality improvement, and innovation, while also promoting consistency, reliability, and informed decision-making. Their significance extends to both individual skill development and the success of organizations and industries as a whole.

Applications have become integral to modern life, transforming the way we work, communicate, learn, and entertain ourselves. Their significance extends to various domains, bringing convenience, efficiency, and innovation to individuals, businesses, and society as a whole.

Resources are crucial for sustenance, economic growth, technological progress, and societal well-being. They impact various aspects of human life and are essential for building and maintaining prosperous and thriving societies. Responsible management and utilization of resources are key to ensuring their long-term significance and availability for future generations.

Overall, this edited book offers a comprehensive and interdisciplinary overview of strategies, techniques, applications and resources. The articles presented here provide a rich source of information and ideas for researchers, students, practitioners, and policymakers interested in sustainability, transformation, growth and excellence. We hope that this book will inspire further research, discussion, and action towards a more progressive future for all.

- Dr. Arceloni Neusa Volpato
- Dr. B. Balaji
- Dr. S. Karthikeyan
- Dr. Divya R. Panjwani
- **Editors**

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CONTENTS

Maximizing Efficiency and Sustainability in Concrete Building Frames through Multi-Objective Simulated Annealing

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Abstract

In the construction business, concrete building frames are a standard structural system. It is essential to optimize their design to achieve structural efficacy, cost-effectiveness, and environmental sustainability. To improve the performance of concrete building frames, this study investigates the use of Multi-objective Simulated Annealing (MOSA), a potent optimization approach. The paper thoroughly analyses MOSA, its integration with concrete frame design, and its potential advantages in getting the best results while juggling competing goals. The multiobjective optimization of reinforced concrete framed structures, which are often utilized in building construction, is the topic of this research. It demonstrates the effectiveness of a multiobjective simulated annealing (MOSA) technique used to solve two objective functions related to the financial cost of the frames and the number of bars in the reinforcement arrangement. Since bar structures with fewer bars are simpler to create, the latter aim is significant regarding the frame's constructability. The IS-456 for Structural Concrete is followed in the evaluation of solutions. Using an internal matrix technique, stress resultants and envelopes of framed structures are calculated. The national codes for building structures are followed while determining design loads.

Keywords: Constructability, Multi-objective Simulated Annealing (MOSA), Optimization, Reinforced concrete framed structures.

1. Introduction

Artificial intelligence (AI) has been used in various fields, including optimizing complex problems since the 1950s. However, the design of cost-effective concrete structures still heavily relies on the expertise of structural professionals. The design of concrete structures involves selecting variables like material grades, cross-sectional dimensions, and reinforcement, which could benefit from AI. Currently, most design processes adhere to established norms for these variables. After defining the structure, stress analysis and reinforcement calculations are performed to meet safety standards. If the initial choices are insufficient, adjustments are made through trial and error, emphasizing the role of the structural designer's experience in ensuring both safety and cost-effectiveness in construction.

Structural optimization methods can be broadly categorized into two groups: exact methods and heuristic methods. The traditional approach, exact methods, relies on iterative techniques of linear programming to compute optimal solutions [1,2]. The second major group, heuristic methods, has evolved in recent times with the advancement of artificial intelligence procedures. This category encompasses various search algorithms [3-6], such as genetic algorithms, simulated annealing, threshold accepting, tabu search, ant colonies, and more. These methods have demonstrated success in diverse fields beyond structural engineering [7]. Despite their simplicity, they demand significant computational resources due to the numerous iterations involved in evaluating the objective function and checking structural constraints.

In the early stages of heuristic optimization applied to structures, notable contributions include the work of Jenkins [8-9] and Rajeev and Krishnamoorthy [10] in 1991-1992. Both authors utilized genetic algorithms to optimize the weight of steel structures. Concerning reinforced concrete (RC) structures, early applications from 1997 include the research by Coello et al [11], who employed genetic algorithms for the economic optimization of RC beams. More recently, there has been a growing body of work on RC applications [12-15], focusing on the optimization of RC beams and building frames using genetic algorithms. Furthermore, our research group has applied simulated annealing and threshold acceptance in recent studies to optimize various structural elements, including walls, portal and box road frames, and building framed structures [16-18].

This study focuses on building frames, which are typically integral components of buildings' structural systems. Building frames consist of horizontal beams with spans ranging from 5.00 to 12.00 meters, supporting the vertical loads from the floors and transferring them to vertical columns with heights between 3.00 to 6.00 meters. While they are designed to handle moderate horizontal loads, higher levels of horizontal loading are usually redirected to adjacent shear walls. Building frames are meticulously engineered to withstand the loads specified in building codes and must meet all the required limit states for reinforced concrete (RC) structures.

The approach employed in this research begins with the development of a computational module for evaluation, where variables such as dimensions, materials, and steel reinforcement are considered. This module calculates both the cost and the quantity of longitudinal bars for a given solution, while also verifying compliance with all relevant limit states. Subsequently, the method utilizes Multiobjective Simulated Annealing, abbreviated as MOSA, to explore the solution space. The goal is to identify the Pareto set of combinations pertaining to the two primary objectives: the economic cost of the structure and the number of longitudinal bars. The latter objective is of particular significance, as structures with fewer longitudinal bars are easier to construct.

2. Technique for proposed multiobjective optimisation

The structural concrete multiobjective optimization problem addressed in this study involves two primary objectives. Firstly, it aims to minimize the cost function, denoted as f1 in equation (1). Additionally, it seeks to minimize function f2 in equation (2), which quantifies the number of longitudinal bars used in the structure. Feasible solutions are those that adhere to the constraints specified in equation (3).

$$f_1(x_1,x_2,...x_n) \square \square p_i \square m_i(x_1,x_2,...,x_n) \tag{1}$$
$$i \square 1,r$$

$$f_2(x_1,x_2,...x_n) \square \square b_i(x_1,x_2,...,x_n) \tag{2}$$
$$i \square 1,s$$

$$g_j(x_1,x_2,...............n) \square 0 \tag{3}$$

Note that the objective function in expression (1) is the sum of unit prizes multiplied by the measurements of construction units (concrete, steel, formwork, etc). And that the restrictions in expression (3) are all the service and ultimate limit states that the structure has to satisfy. Unitprices considered for the frames below are given in Table 1.

Table 1 *Unit prices considered for RC framed structures (DSR Volume 1, 2021)*

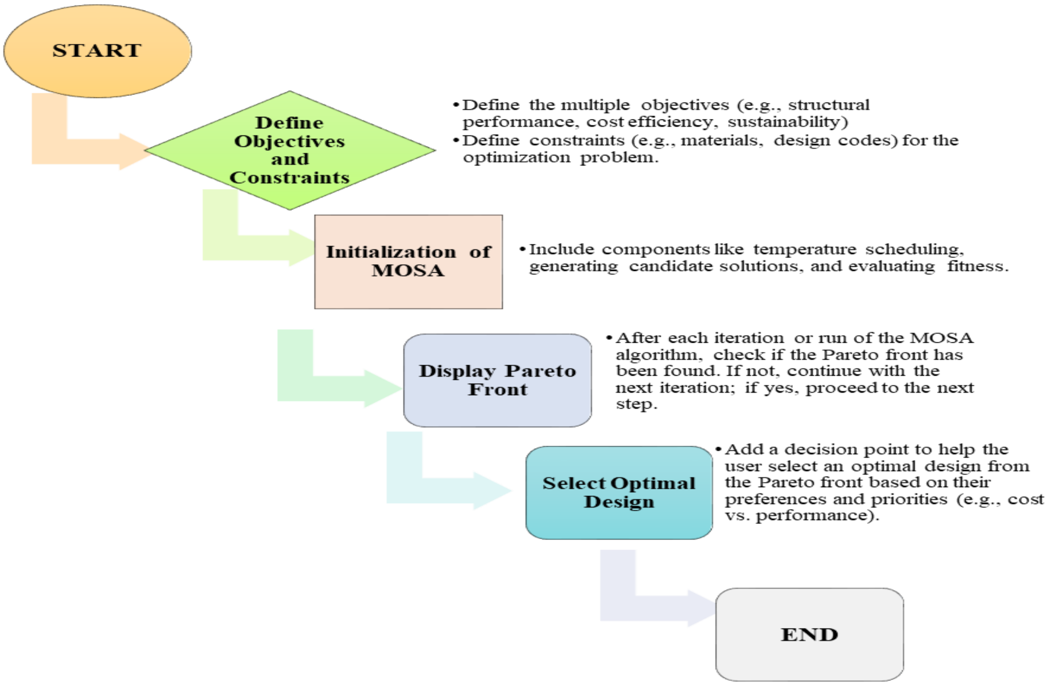
Unit	Description	Cost (INR)
Kg.	Steel B-400	49
m^3	Concrete HA-25	7783.65
m^2	Formwork in beams	804.25

2.1 Multiobjective simulated annealing

The flowchart depicting the multiobjective simulated annealing algorithm proposed in this study is illustrated in Figure 1. This algorithm's fundamental concepts were initially introduced by Suppapitnarm et al. in 2000 [23], often referred to in the literature as the SMOSA algorithm. For a comprehensive examination of alternative MOSA algorithms, please refer to other sources [24]. Here is a summary of the steps followed by the algorithm:

1. It begins with the generation of a random feasible solution.
2. Initial temperatures are assigned to the two objective functions: the structure's cost and the number of bars, following Medina's method, as explained earlier for the single-objective simulated annealing.
3. After adjusting the initial temperatures, a small random adjustment is made to the variable values, resulting in a new working solution.
4. This working solution is assessed against the Pareto condition, which is met when the solution is not dominated by any previous element in the Pareto set of solutions.
5. If it satisfies the Pareto condition and passes the structural constraints check, the current solution is updated and added to the Pareto list.
6. If the solution does not meet the Pareto condition, the algorithm checks the SMOSA acceptance criterion. This criterion is met when either the cost and the number of bars are lower than in the previous solution or when the square root of the factorial of exp(-Δfi/Ti) is greater than a random number between 0 and 1. In the latter case, the Pareto set is not improved, but the working solution becomes the starting point for the next iteration.
7. The temperatures for the two objective functions are gradually reduced after a certain number of iterations referred to as Markov chains.
8. Periodically, the algorithm restarts from one of the extreme solutions in the Pareto set, with this selection also being made randomly.

It's worth noting that the algorithm outlined in Figure 1 shares a key characteristic with the original SMOSA algorithm, as it only accepts feasible solutions.



- Define the multiple objectives (e.g., structural performance, cost efficiency, sustainability)
- Define constraints (e.g., materials, design codes) for the optimization problem.
- Include components like temperature scheduling, generating candidate solutions, and evaluating fitness.
- After each iteration or run of the MOSA algorithm, check if the Pareto front has been found. If not, continue with the next iteration; if yes, proceed to the next step.
- Add a decision point to help the user select an optimal design from the Pareto front based on their preferences and priorities (e.g., cost vs. performance).

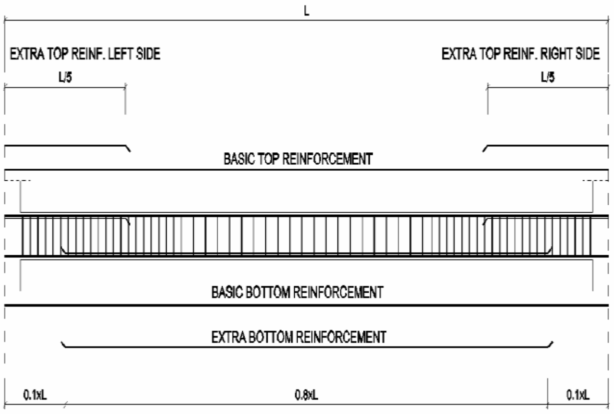
Fig. 1 *Flow-chart of the proposed MOSA procedure*

3. Building frameworks for RC buildings using MOSA

The study focuses on reinforced concrete (RC) frames used in building construction, specifically a symmetrical frame with 2 bays and 4 floors, involving a total of 81 distinct design variables. These variables cover aspects like the choice of reinforcing steel, concrete types for columns and beams (with strength variations from 25 MPa to 50 MPa in 5 MPa increments), cross-sectional dimensions of columns and beams, and configurations of reinforcement steel.

For the beams, they follow a standard longitudinal reinforcement pattern, including top and bottom bars along with additional positive and negative reinforcements of fixed lengths. Beam stirrups are divided into left, central, and right zones for transverse reinforcement. Columns offer 330 potential values for longitudinal reinforcement, ranging from 4Φ12 to 34Φ25, along with 21 possible values for transverse reinforcement.

It's essential to highlight the substantial number of variables needed to model such structures, with 81 design variables for the smaller RC frame in Figure 2 as mentioned earlier. Furthermore, considering a more typical frame with 4 bays and 8 floors would result in 377 design variables. This significant increase in variables presents



notable challenges for future developments, particularly when considering computational runtime, as indicated below for the example involving 81 variables.

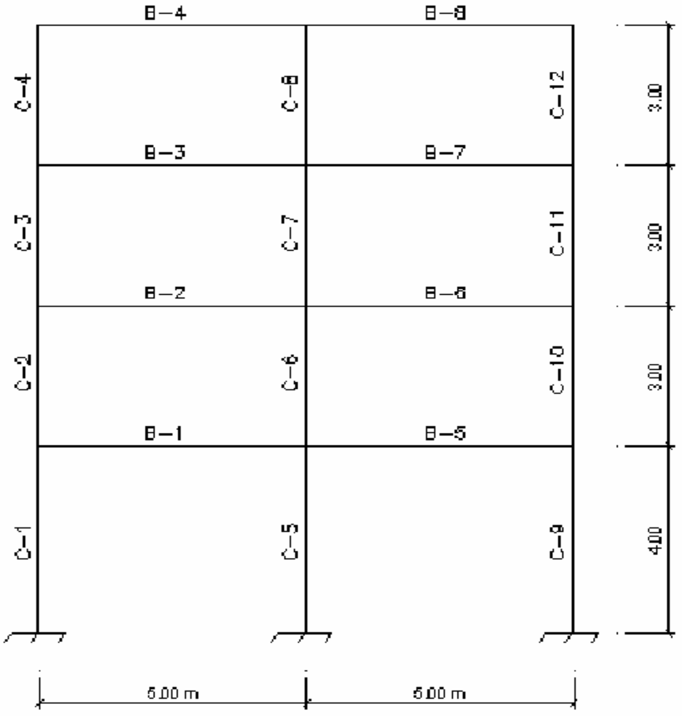


Fig. 2 *Typical RC building frame of 2 bays and 4 floors*

This analysis focuses on several key parameters, including the horizontal bay spans, column heights, vertical and horizontal loads, and safety coefficients. The structural constraints adhere to established Indian standards for this type of structure, encompassing checks for serviceability and ultimate limit states related to flexure, shear, and instability due to vertical and horizontal loads. The vertical loads consist of a uniform distributed load totalling 35 kN/m, comprising 7.00 kN/m2 for self-weight and live load, with a 5.00 m spacing between parallel frames. Wind loads contribute a uniform distributed load of 4.5 kN/m. Stress resultants and reactions are calculated using an internal matrix method program that employs a 2-D mesh. Deflections are restricted to 1/250 of the horizontal span for the total load and 1/400 for active deflection, which is measured after construction and can be influenced by vertical displacements. The prices considered for this analysis are detailed in Table 1.

Fig. 3 *Typical longitudinal reinforcement bars of the beams of RC building frames*

The MOSA algorithm was implemented in Visual Basic 6.0, with typical runs for the RC frame with 2 bays and 4 floors in Figure 3 taking up to 10.9 hours on a Pentium IV computer with a 3.20 GHz processor. The recommended calibration parameters for the MOSA algorithm include Markov chains or cycles of 70,000 iterations and a cooling coefficient of 0.80. The most effective strategy involved random variations in 3 or up to 3 variables out of the 81 variables in the problem.

Figure 4 illustrates the progression of the Pareto set at various iteration counts: 50,000, 500,000, 1,500,000, and 2,150,000. Additionally, Figure 5 and Table 2 provide detailed results for the solution with the fewest number of bars for the RC frame with 2 bays and 4 floors. The steel reinforcement used has a characteristic strength of 500 MPa. Columns are constructed with C35, C25, C40, and C30 concrete for the first to fourth floors, while beams use C30 concrete for all four floors, except the second floor, which employs C40 concrete.

The cost of this MOSA solution is INR 330045.54, compared to the most cost-effective solution at INR 314959.75 (a 4.8% cost increase). In terms of the number of bars, the solution with fewer bars has 84, while the most cost-effective solution has 97 bars (a 15.5% increase in the number of bars). Importantly, the cost increase is justified by the improvement in the constructability of the structure.

Table 2 *Beam results of the MOSA solution with a lower number of bars*

Member No. & Position		Width (mm)	Depth (mm)	Ast Required (mm2)	Total Area (mm2)	Top Bar Combination	Cost (Rs)	Embodied Carbon (kg Co2)
2	Node1	285	350	334.8806	340	12-1 12-2		
2	Center	285	350	-415.107	418	10-1 12-3		
2	Node2	285	350	693.5891	698	10-2 12-2 20-1	8040.12	114.64
4	Center	250	330	-553.1433388	604	16-1 16-2		
4	Node1	250	330	319.5857242	340	12-1 12-2		
4	Node2	250	330	241.1771626	271	10-2 12-1	7575.46	86.54
5	Center	255	360	-450.3872846	472	10-2 20-1		
5	Node1	255	360	457.3703539	472	10-2 20-1		
5	Node2	255	360	374.8431902	428	12-2 16-1	7226.23	95.26
7	Node1	250	320	375.46	392	10-1 12-2		
7	Center	250	320	-456.236	475	10-2 12-2		
7	Node2	250	320	510.68	517.26	10-2 12-2 16-1	47240.308	81.42
9	Center	300	400	-316.7599479	340	12-1 12-2		
9	Node1	300	400	879.1267251	893	16-2 25-1		
9	Node2	300	400	370.131772	428	12-2 16-1	8234.16	116.45

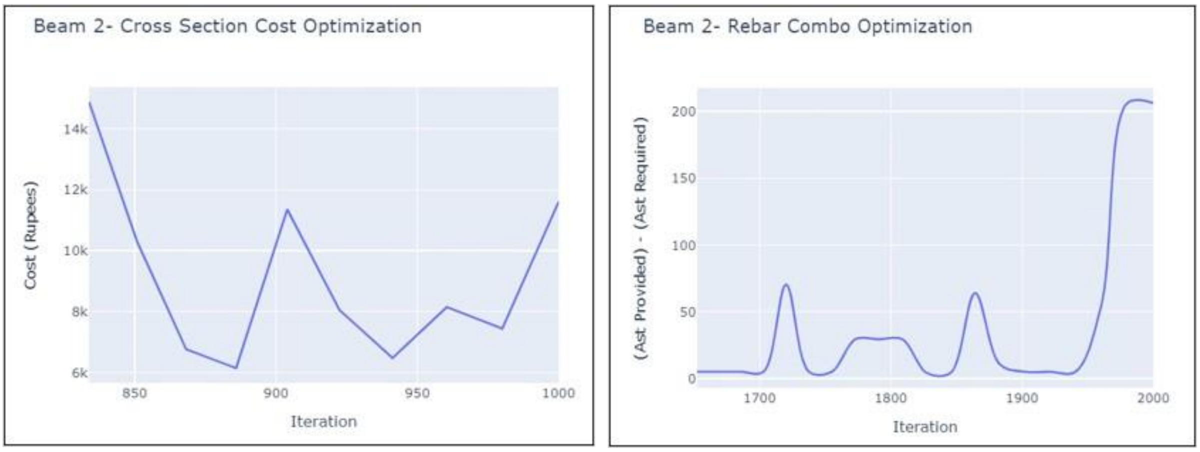


Fig. 4 *Optimization Trend over the iteration for beam element*

4. Conclusion

In summary, this study focuses on optimizing concrete building frame, a vital element in the construction industry, with a primary aim of enhancing structural efficiency, cost-effectiveness, and environmental sustainability. The research investigates the application of Multi-objective Simulated Annealing (MOSA) for achieving these objectives and provides an in-depth analysis of its integration into concrete frame design. The study centres on multiobjective optimization for reinforced concrete framed structures commonly used in construction, demonstrating the effectiveness of MOSA in addressing financial cost and reducing the number of bars in the reinforcement arrangement to simplify constructability. Adherence to structural standards and codes ensures rigour in the evaluation process. Overall, this research emphasizes the significance of optimizing concrete building frames and underscores MOSA's potential as a valuable tool for achieving cost-effective and constructible designs while meeting essential structural criteria, contributing to more sustainable and efficient construction practices. Based on the findings presented above, several key conclusions can be drawn:

- The investigation of RC building framed structures highlights the promising potential of the MOSA algorithm for effectively optimizing such structures with multiple objectives.
- The results provide an illustrative case in which a relatively modest cost increase of 4.8% is associated with a significant 15.5% reduction in the number of bars. This suggests that it is possible to design structures that are more constructible while incurring cost increases that remain practical and acceptable in real-world construction scenarios.

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