

Development of a scheduling model in the construction industry based on project quality under limited resource constraints

Mahyar AzizKhani¹, Davood sedaghat shayegan^{*2}, Ali Asghar Amirkardoost³

¹Ph.D. candidate, Department of Civil Engineering, RO.C., Islamic Azad University, Roudehen, Iran

² Department of Civil Engineering, RO.C., Islamic Azad University, Roudehen, Iran.

³ Department of Civil Engineering, RO.C., Islamic Azad University, Roudehen, Iran.

ABSTRACT

Project scheduling in the construction industry, especially under resource constraints, has always been a major challenge in project management. In this study, a multi-objective model was presented for scheduling multi-state projects with limited resources, which, in addition to time and cost, also considers the quality of activity execution as an independent objective function. In line with the NP-hard nature of this problem, two meta-heuristic algorithms, PSO and NSGA-III, were used to generate 3D Pareto fronts. The results showed that the NSGA-III algorithm was able to provide answers with relatively low time and cost-effective costs in both resource scenarios; especially in the second case, where the lowest cost of 3572 million rials for a period of 21 days and a quality of 69% was obtained. In contrast, PSO outperformed in the first case in achieving higher quality, producing solutions with a quality of 74% and a similar duration of 17 days, albeit at a higher cost (4304 million rials). Pareto front analysis showed that PSO produced a higher diversity of responses and provided balanced combinations among the three objectives, while NSGA-III tended to produce uniform responses with a focus on cost reduction. The main innovation of this research is the independent inclusion of the quality function in the scheduling model and the in-depth comparison of the performance of the two algorithms under different resource conditions, which can be used as an efficient tool for project decision makers to select the optimal option based on strategic priorities.

KEYWORDS: Scheduling model, project scheduling, time-cost optimization, resource constraints, meta-heuristic algorithm.

* Corresponding Author: Email: da.sedaghat@iau.ac.ir

1. Introduction

Project scheduling under resource constraints has long been a fundamental and challenging problem in the construction industry. The ability to efficiently allocate limited renewable and non-renewable resources while simultaneously achieving desirable levels of project duration, cost, and quality has a significant influence on overall project success [1,2]. In practical construction environments, projects often encounter budget limitations, shortages of skilled labor, and fluctuations in material availability, all of which can adversely affect project quality and productivity [3]. Studies by FMI (2021) and the Iranian Building and Housing Research Center (2020) have shown that in projects with severe financial constraints, quality degradation of up to 35% is commonly observed, while early cracking in concrete structures increases by nearly 28% compared to well-funded projects [4]. Consequently, the need for multi-objective optimization models that can balance time, cost, and quality under resource constraints has become increasingly critical. Traditional approaches to the Resource-Constrained Project Scheduling Problem (RCPSPP) mainly focused on minimizing project duration or cost independently, without adequately incorporating quality as a distinct objective [5]. However, in real-world construction projects, trade-offs among time, cost, and quality are inevitable. Accelerating project completion often requires increased resources and direct costs, while reducing cost may result in compromised quality or extended duration [6]. Hence, the introduction of multi-mode resource-constrained project scheduling problems (MRCPSPP) allows each activity to be executed through multiple alternative modes, each with different resource requirements, durations, and associated quality levels. This study develops an enhanced multi-objective optimization model for scheduling construction projects under daily renewable and non-renewable resource limitations. The proposed model introduces quality as an independent optimization objective alongside time and cost, thus providing a realistic representation of the trade-offs faced by project managers in practice. To solve this inherently NP-hard problem, two advanced metaheuristic algorithms, Particle Swarm Optimization (PSO) and Non-Dominated Sorting Genetic Algorithm III (NSGA-III) were implemented and comparatively evaluated [7]. The novelty of this research lies in

integrating quality as a separate optimization function within an MRCPSPP framework and providing an in-depth comparison of the two algorithms under different resource scenarios.

2. Methodology

The proposed model was formulated as a multi-objective optimization problem with three primary objectives:

- (i) minimization of total project duration,
- (ii) minimization of total cost
- (iii) maximization of execution quality.

Each project consists of n activities, denoted as nodes within an Activity-on-Arrow (AOA) network, with defined precedence constraints. Each activity can be executed in one of several modes, each mode representing a unique combination of required renewable and non-renewable resources, activity duration, and quality level. The decision variables determine the start time and execution mode of each activity, ensuring that precedence and resource constraints are not violated. To ensure feasibility, several constraints were imposed:

- each activity is executed in exactly one mode;
- resource usage does not exceed daily availability of renewable or non-renewable resources;
- precedence constraints are strictly maintained;
- binary decision variables x_{jmt} and y_{jmt} indicate activity completion at time t and execution mode m , respectively.

A minimum overall project quality threshold of 69% was introduced to prevent the algorithms from selecting low-cost but poor-quality solutions. Two metaheuristic algorithms were implemented to solve the model:

(a) Particle Swarm Optimization (PSO)

PSO was employed using a numeric encoding scheme for the sequence and mode of activities. Violation of constraints was

managed through penalty functions. The algorithm iteratively updates particle positions and velocities based on local and global best solutions, allowing convergence toward an optimal Pareto front [8].

(b) NSGA-III Algorithm (NSGA-III)

NSGA-III, an extension of NSGA-II, introduces a set of *reference points* to enhance the diversity of solutions in many-objective problems. It sorts individuals based on non-domination ranking and selects elites using reference vectors that distribute solutions uniformly along the Pareto front [9]. Parameter calibration for both algorithms was performed via trial-and-error. For PSO, the best configuration included a population size of 150, 200 iterations, and an inertia weight of 0.8. For NSGA-III, the optimal setup used a population of 100, 200 iterations, a crossover rate of 0.7, and a mutation rate of 0.1. The model was validated using a 10-activity test project, each with multiple execution modes and resource combinations. Two resource availability scenarios were tested one with higher resource supply (Scenario 1) and another with more restrictive conditions (Scenario 2). Both algorithms were implemented in MATLAB, and the resulting Pareto fronts were analyzed for comparative performance evaluation.

3. Results and Discussion

The results demonstrated that both algorithms successfully generated feasible and diverse Pareto-optimal solutions, effectively balancing the three conflicting objectives. In Scenario 1 (higher resource availability), PSO achieved the best performance in terms of quality. The highest recorded quality level was 74%, corresponding to a 17-day duration and a total cost of 4304 million Rials. NSGA-III, in the same scenario, produced comparable results with slightly lower quality (71%) and shorter project duration (18 days) at a reduced cost of 4165 million Rials. Overall, PSO exhibited superior exploration capabilities, achieving broader diversity across Pareto solutions. In Scenario 2 (limited resources), NSGA-III outperformed PSO in cost efficiency. The optimal solution from NSGA-III achieved the lowest total cost of 3572 million Rials, with a project duration of 21 days and a quality of 69%.

PSO, in comparison, delivered solutions of similar time and quality but at slightly higher costs (up to 3941 million Rials). The three-dimensional Pareto front analysis revealed distinct behavioral characteristics of the algorithms. PSO tended to produce a wider spread of solutions, including high-quality-high-cost combinations, which are valuable when quality is prioritized over budget. In contrast, NSGA-III generated more uniform and stable fronts, emphasizing cost minimization and consistency under constrained resources [10]. Figure-based analysis in Fig. 1 indicated that both algorithms achieved convergence after approximately 150 iterations, with PSO exhibiting faster improvement during the early iterations due to its collective learning mechanism. However, NSGA-III showed greater stability in the later stages, maintaining diversity and avoiding premature convergence. A comparative summary of performance metrics is presented in Table 1.

Table 1: A comparative summary of performance metrics

Criterion	Superior Algorithm	Key Values
Minimum project duration	Both (17 days)	Comparable
Minimum cost	NSGA-III	3572 million Rials
Maximum quality	PSO	74%
Pareto diversity	PSO	Broader spread
Stability under constraints	NSGA-III	Higher consistency

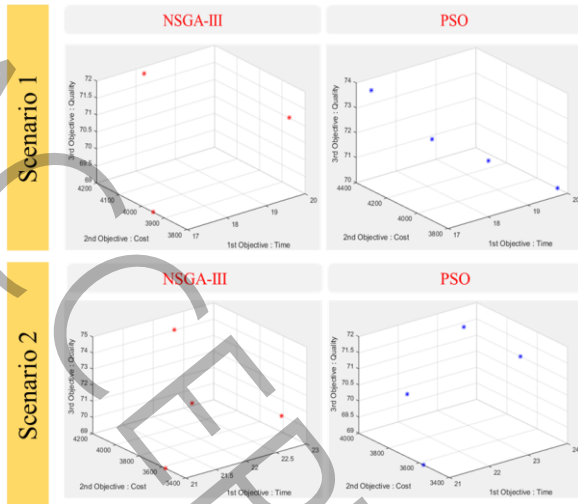


Fig. 1: The solution obtained from the NSGA-III and PSO algorithms

References

- [1] Merkle, D., Middendorf, M., & Schneck, H. (2002). Ant colony optimization for resource-constrained project scheduling. *IEEE transactions on evolutionary computation*, 6(4), 333-346.
- [2] Zhang, H., Li, H., & Tam, C. M. (2006). Particle swarm optimization for resource-constrained project scheduling. *International journal of project management*, 24(1), 83-92.
- [3] Zhang, H., Li, X., Li, H., & Huang, F. (2005). Particle swarm optimization-based schemes for resource-constrained project scheduling. *Automation in construction*, 14(3), 393-404.
- [4] Rogalska, M., Bożejko, W., & Hejducki, Z. (2008). Time/cost optimization using hybrid evolutionary algorithm in construction project scheduling. *Automation in Construction*, 18(1), 24-31.
- [5] Balouka, N., & Cohen, I. (2021). A robust optimization approach for the multi-mode resource-constrained project scheduling problem. *European journal of operational research*, 291(2), 457-470.
- [6] Wang, L., & Zheng, X. L. (2018). A knowledge-guided multi-objective fruit fly optimization algorithm for the multi-skill resource constrained project scheduling problem. *Swarm and Evolutionary Computation*, 38, 54-63.
- [7] Guo, K., & Zhang, L. (2022). Multi-objective optimization for improved project management: Current status and future directions. *Automation in Construction*, 139, 104256.
- [8] Xie, L. L., Chen, Y., Wu, S., Chang, R. D., & Han, Y. (2024). Knowledge extraction for solving resource-constrained project scheduling problem through decision tree. *Engineering, Construction and Architectural Management*, 31(7), 2852-2877.
- [9] Yu, Ze, Chuxin Wang, Yuanyuan Zhao, Zhiyuan Hu, and Yuanjie Tang. "Linear Project-Scheduling Optimization Considering a Reverse Construction Scenario." *Applied Sciences* 13, no. 16 (2023): 9407.
- [10] Zohrehvandi, M., Zohrehvandi, S., Khalilzadeh, M., Amiri, M., Jolai, F., Zavadskas, E. K., & Antucheviciene, J. (2024). A Multi-Objective Mathematical Programming Model for Project-Scheduling Optimization Considering Customer Satisfaction in Construction Projects. *Mathematics*, 12(2), 211.