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Multi-Objective Optimization of Time, Cost, Energy, and Risk in Bridge Construction Projects Using Teaching-Learning-Based Optimization

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Abstract: The proposed model integrates four conflicting objectives—minimizing project duration, cost, energy consumption, and risk—into a unified decision-making platform. The Multi-Objective Teaching-Learning-Based Optimization (MOTLBO) algorithm is employed due to its superior convergence, solution diversity, and low parameter dependence. A real-world case study of a reinforced concrete girder bridge is used to validate the model, demonstrating its capability to generate 18 Pareto-optimal solutions across varied execution modes.

Keywords*: *Teaching-Learning-Based Optimization (TLBO); MOTLBO; Time-cost-energy-risk trade-off; Integrated Project Delivery (IPD); Weighted Sum Method (WSM).

I. INTRODUCTION

As infrastructure projects become increasingly complex and sustainability-driven, the need for robust, adaptable, and multi-dimensional optimization frameworks becomes more critical. The MOTLBO-based model proposed in this study addresses this need by offering a validated, efficient, and practical solution for optimizing bridge construction projects under the IPD framework. It aligns with global priorities such as low-carbon development, resilient infrastructure, and efficient public investment, thereby contributing significantly to both academic literature and construction industry practices.

A. Research Objectives

1) To formulate a discrete-time multi-objective optimization model that incorporates project duration, cost, energy consumption, and construction risk as key performance indicators.
2) To implement and customize the Multi-Objective Teaching-Learning-Based Optimization (MOTLBO) algorithm to efficiently solve the formulated model under real-world construction constraints.
3) To apply the proposed MOTLBO-based optimization framework to a real-world reinforced concrete girder bridge project and generate Pareto-optimal trade-off solutions.
4) To validate the performance of the MOTLBO algorithm by comparing it with benchmark multi-objective optimization algorithms, including NSGA-II, NSGA-III, MOACO, and MOPSO, using metrics such as Hypervolume (HV), Inverted Generational Distance (IGD), Spacing (Sp), and R^2 accuracy.
5) To assist decision-makers in selecting the most balanced solution using a decision-support tool based on the Weighted Sum Method (WSM), accounting for stakeholder priorities and project-specific goals.

II. LITERATURE REVIEW

The review of existing literature reveals significant advancements in the application of multi-objective optimization (MOO) techniques in construction project management, particularly in addressing time and cost trade-offs through algorithms like NSGA-II, PSO, and GA. However, a growing emphasis on sustainability and safety has highlighted the need to incorporate energy consumption and risk mitigation into project optimization frameworks. Despite efforts in energy-aware scheduling and risk-based modeling, very few studies offer an integrated framework that simultaneously optimizes all four critical objectives—time, cost, energy, and risk.

III. PROBLEM FORMULATION

The goal of this multi-objective optimization problem is to simultaneously optimize four conflicting project performance criteria—namely, time, cost, energy consumption, and risk—in the context of bridge construction scheduling. Each of these objectives is formulated mathematically to guide the optimization process.

IV. PROPOSED MOTLBO FRAMEWORK

The MOTLBO framework offers a robust optimization approach for bridge construction projects, addressing multiple conflicting objectives. It simultaneously optimizes time, cost, energy, and risk, promoting sustainable construction. The teaching-learning mechanism enables faster convergence compared to conventional evolutionary algorithms, improving overall computational efficiency. Additionally, discrete decision-making ensures practical selection of execution modes for construction activities, making the framework suitable for large-scale projects with complex dependencies. Its comparative superiority over NSGA-II, NSGA-III, MOACO, and MOPSO in terms of solution accuracy and efficiency establishes MOTLBO as a highly effective optimization technique for construction scheduling and resource allocation. The flowchart for MOTLBO is presented as Figure 4.1.

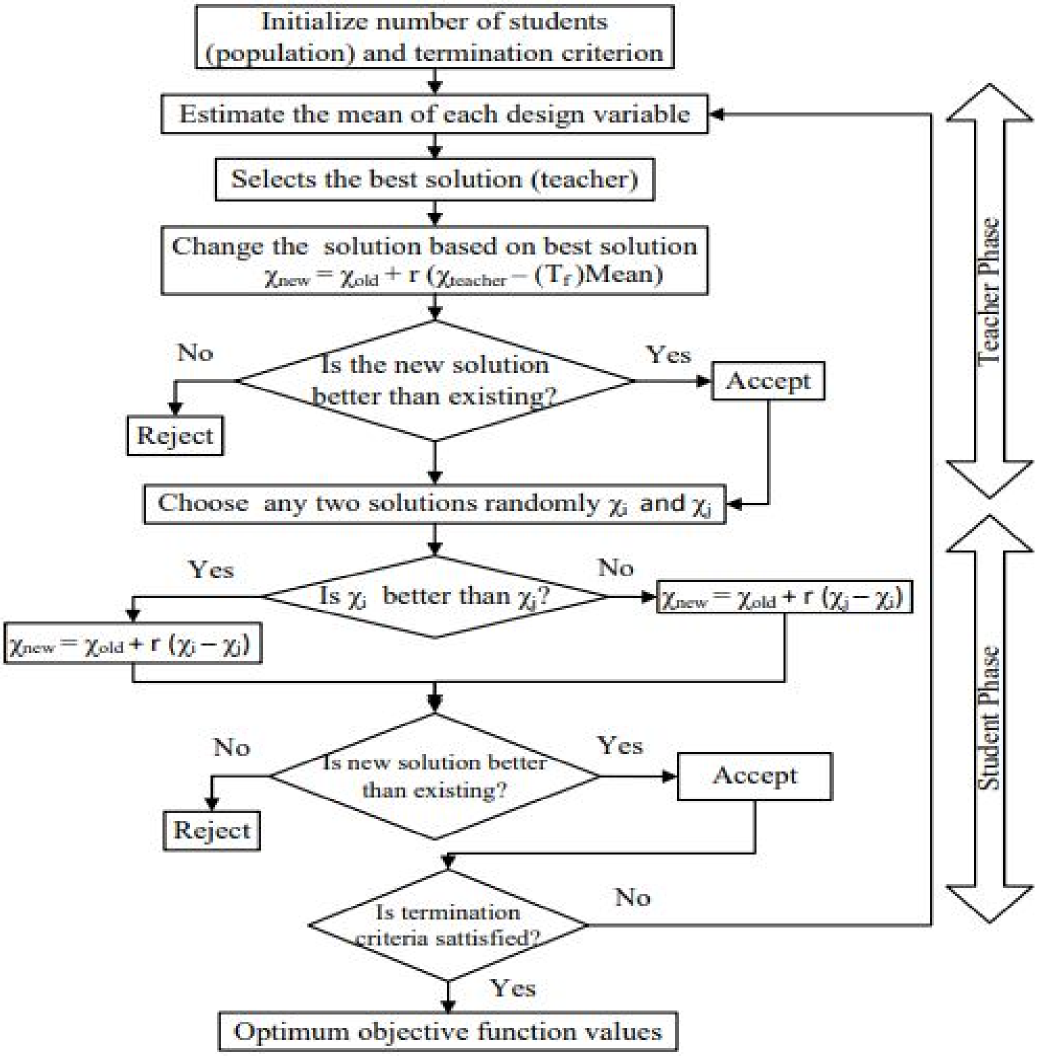


Figure 4.1. Workflow of MOTLBO Framework

The validation of the MOTLBO model for bridge construction optimization was conducted using the R² score, which measures how well the model explains the variability in the four key objectives: time, cost, energy, and risk.

V. CASE STUDY: BRIDGE CONSTRUCTION PROJECT

The bridge construction project under study is a Reinforced Concrete Girder Bridge, designed to span 300 meters with a width of 12 meters. It consists of six spans, each measuring 50 meters, and utilizes reinforced concrete for both the deck and piers, ensuring structural durability and long-term performance.

This study aims to achieve an optimal balance between efficiency, sustainability, and risk mitigation, ensuring that the project is completed within budget and on schedule while minimizing environmental impact (Table 5.2).

Table 5.2. Activity Input Data

Activity ID	Activity	Predecessor	Execution Mode	Time (days)	Cost (INR)	Energy	Risk
A	Site Preparation	-	1-Standard	15	12,00,000	264.07	0.451
			2-Accelerated	10	15,00,000	447.71	0.062
			3-Eco-Friendly	18	13,00,000	322.52	0.075
B	Foundation Excavation	A	1-Standard	25	38,00,000	394.26	0.362
			2-Accelerated	18	46,00,000	388.47	0.213
			3-Eco-Friendly	30	42,00,000	286.4	0.176
C	Piling	B	1-Standard	40	85,00,000	416.55	0.442
			2-Accelerated	30	1,00,00,000	288.25	0.354
			3-Eco-Friendly	50	92,00,000	101.5	0.112
D	Pier Construction	C	1-Standard	50	1,20,00,000	260.73	0.144
			2-Accelerated	40	1,40,00,000	242.17	0.423
			3-Eco-Friendly	60	1,30,00,000	432.76	0.244
E	Deck Slab Installation	D	1-Standard	70	2,00,00,000	145.49	0.323
			2-Accelerated	55	2,40,00,000	244.52	0.133
			3-Eco-Friendly	85	2,15,00,000	350.16	0.068
F	Precast Beam Placement	E	1-Standard	30	65,00,000	158.55	0.352
			2-Accelerated	25	78,00,000	492.2	0.213
			3-Eco-Friendly	35	70,00,000	308.33	0.322
G	Pavement Work	F	1-Standard	20	50,00,000	203.56	0.084
			2-Accelerated	15	60,00,000	125.1	0.472
			3-Eco-Friendly	25	55,00,000	120.91	0.474
H	Guard Rail Installation	G	1-Standard	15	28,00,000	186.01	0.132
			2-Accelerated	12	33,00,000	452.08	0.458
			3-Eco-Friendly	18	30,00,000	229.0	0.447
I	Electrical & Lighting Work	G	1-Standard	20	45,00,000	359.81	0.224
			2-Accelerated	15	55,00,000	123.82	0.142
			3-Eco-Friendly	25	48,00,000	285.38	0.375
J	Landscaping	H, I	1-Standard	10	18,00,000	264.8	0.214
			2-Accelerated	8	20,00,000	253.07	0.322
			3-Eco-Friendly	12	19,00,000	157.86	0.124
K	Final Inspection	J	1-Standard	10	25,00,000	205.49	0.242
			2-Accelerated	7	30,00,000	296.38	0.261
			3-Eco-Friendly	12	27,00,000	257.21	0.133
L	Handover	K	1-Standard	5	12,00,000	150.24	0.462
			2-Accelerated	3	15,00,000	326.52	0.412
			3-Eco-Friendly	6	13,00,000	188.55	0.321

VI. RESULTS AND DISCUSSION

Table 6.1 displays the optimization findings, which include 18 Pareto-optimal solutions for the time-cost-energy-risk trade-off in bridge construction projects that were obtained using the MOTLBO algorithm.

Table 6.1. Obtained Pareto-Optimal Solutions

Solution ID	A	B	C	D	E	F	G	H	I	J	K	L	Time (days)	Cost (INR)	Energy (kWh)	Risk
S1	3	2	3	2	2	1	1	3	1	2	1	2	391	47103230	6369	0.322
S2	1	2	3	3	2	1	2	1	3	2	3	1	353	42558231	6986	0.312
S3	3	1	1	3	2	1	3	3	3	2	2	1	386	46659908	5146	0.197
S4	3	1	3	1	2	3	2	2	3	1	1	2	400	43080389	8219	0.137
S5	1	2	1	3	2	1	1	3	1	2	1	1	395	41661909	7911	0.459
S6	1	2	3	3	3	1	3	1	1	1	1	2	396	42656138	6734	0.46
S7	3	1	3	2	3	1	1	1	2	1	3	2	300	40110078	6843	0.353
S8	2	1	1	1	2	3	2	2	1	2	3	3	318	41915631	5488	0.236
S9	3	1	1	2	3	1	1	3	3	2	2	2	301	46314127	7976	0.24
S10	3	3	3	2	1	1	3	3	3	2	3	3	352	49792712	6959	0.39
S11	3	3	2	2	2	3	3	2	1	3	1	1	343	42008187	7385	0.459
S12	3	3	1	2	1	3	2	3	3	2	2	1	389	41659066	7919	0.455
S13	1	2	2	2	1	3	1	3	3	3	1	1	331	42148815	9736	0.412
S14	3	3	2	2	2	1	3	1	1	1	1	1	369	47355740	6802	0.357
S15	2	2	2	2	3	3	2	3	1	3	3	3	331	44506259	9061	0.134
S16	1	2	1	1	1	3	3	3	3	2	2	1	418	47473915	8369	0.165
S17	2	3	2	3	2	1	3	2	3	1	3	2	367	47658426	5262	0.459
S18	2	2	1	2	1	3	1	2	3	1	3	2	354	46404003	5623	0.343
Mean													360.7	44503709	7154.8	0.327
Standard Deviation													35.1	2832010	1297.3	0.116

The trade-off analysis provides valuable insights into the complex relationships between time, cost, energy, and risk in bridge construction projects. Figures 6.1 to 6.6 illustrate 2D trade-offs, showing how optimizing one objective influences the others.

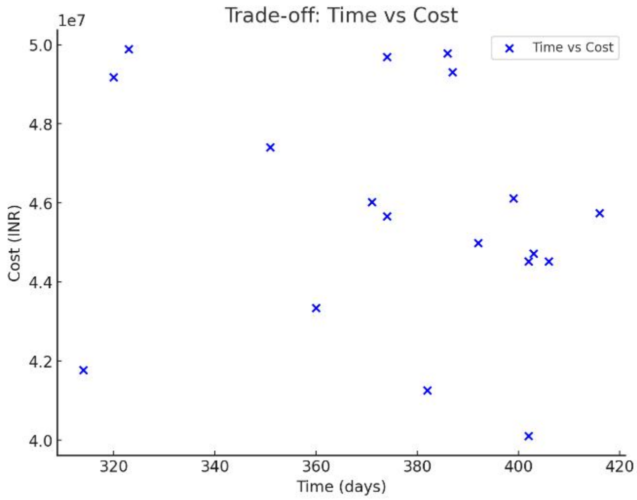


Figure 6.1. Time-Cost Trade-Off

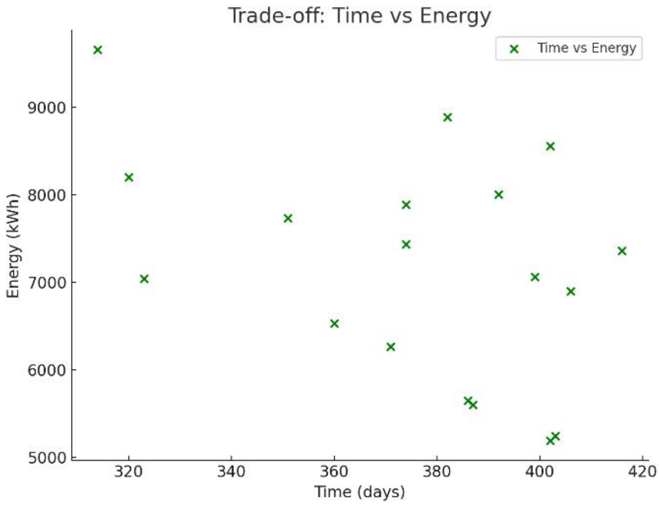


Figure 6.2. Time-Energy Trade-O

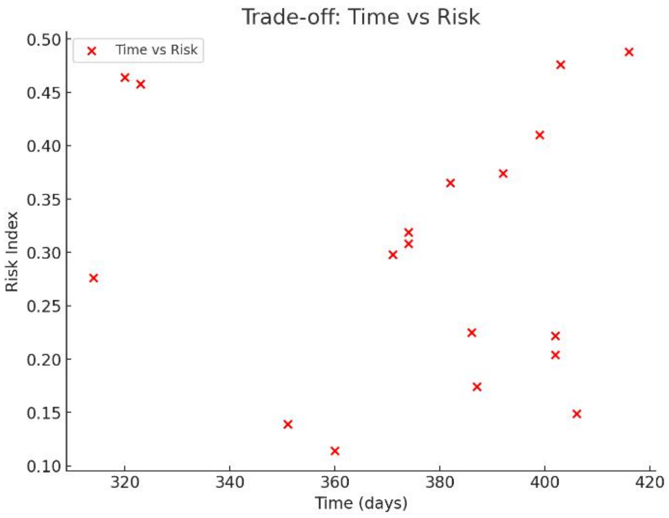


Figure 6.3. Time-Risk Trade-Off

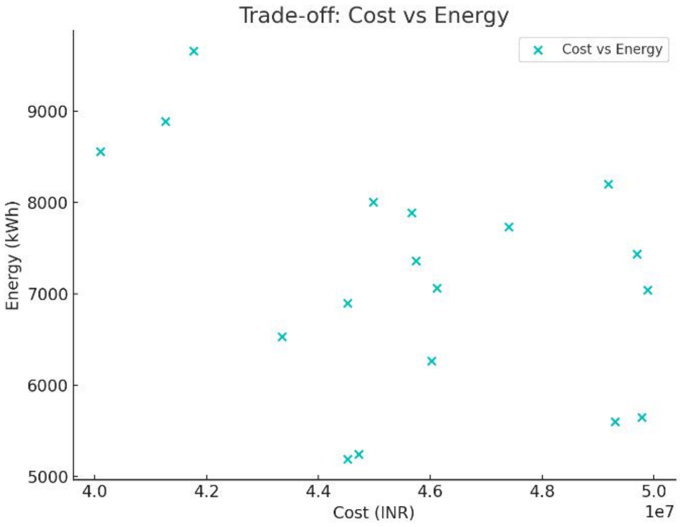


Figure 6.4. Cost-Energy Trade-Off

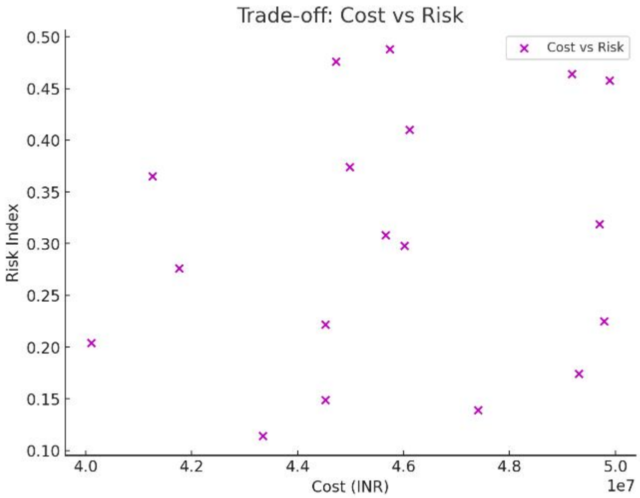


Figure 6.5. Cost-Risk Trade-Off

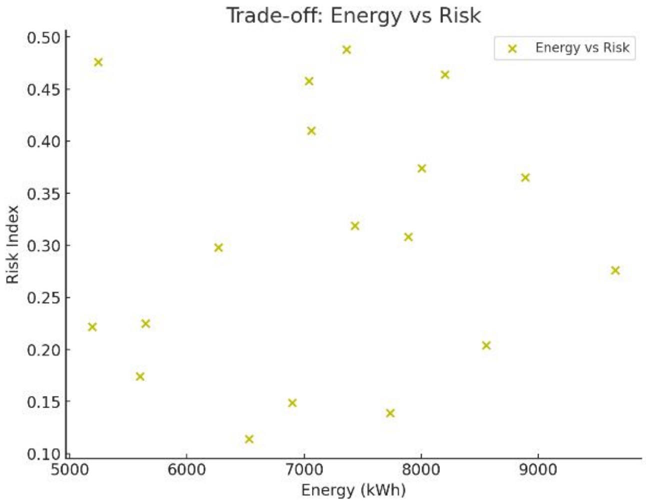


Figure 6.6. Energy-Risk Trade-Off

Table 6.3 provides a comparative analysis of five multi-objective optimization algorithms—NSGA-II (Sharma & Trivedi, 2022), NSGA-III (Trivedi & Sharma, 2023), MOACO (Lakshminarayanan et al., 2010), MOPSO (Agarwal et al., 2024), and MOTLBO (Sethi, Prajapati, et al., 2024)—evaluating their effectiveness in optimizing the Time-Cost-Energy-Risk trade-offs in bridge construction projects. The results indicate that MOTLBO outperforms all other algorithms across multiple key performance metrics.

Table 6.3. Comparison of NSGA-II, NSGA-III, MOACO, MOPSO, and MOTLBO

Algorithm	HV	IGD	Sp	MID	SNS	R^2 (Time)	R^2 (Cost)	R^2 (Energy)	R^2 (Risk)	N	Convergence Rate (CR)	Computational Time (CT) (s)	Diversity Index (DI)
NSGA-II	0.72	0.035	0.45	0.4	0.6	0.9	0.88	0.87	0.86	12	0.85	15	0.5
NSGA-III	0.75	0.032	0.42	0.37	0.65	0.92	0.9	0.89	0.88	14	0.88	14	0.55
MOACO	0.78	0.028	0.4	0.35	0.7	0.94	0.93	0.91	0.9	15	0.9	13	0.6
MOPSO	0.79	0.025	0.38	0.32	0.75	0.96	0.95	0.94	0.92	16	0.92	12	0.65
MOTLBO	0.85	0.02	0.35	0.3	0.8	0.98	0.97	0.96	0.95	18	0.95	10	0.7

VII. CONCLUSIONS

This study developed a discrete time-cost-energy-risk optimization framework for bridge construction projects under the IPD approach using the MOTLBO algorithm. By simultaneously optimizing four conflicting objectives—minimizing project duration, reducing costs, lowering energy consumption, and mitigating construction risk—the framework provides a robust decision-support tool for infrastructure project managers. The case study on a reinforced concrete girder bridge validated the model by generating Pareto-optimal solutions, demonstrating how different execution strategies impact overall project efficiency. The trade-off analysis revealed that accelerated schedules increase energy consumption and risk, whereas eco-friendly execution modes promote sustainability but extend project duration. Correlation analysis further confirmed interdependencies among objectives, particularly the inverse relationship between time and energy and the positive correlation between cost and risk mitigation. The comparative analysis with NSGA-II, NSGA-III, MOACO, and MOPSO demonstrated that MOTLBO outperformed traditional algorithms, achieving superior solution diversity, convergence accuracy, and computational efficiency.

REFERENCES

[1] Agarwal, A. K., Chauhan, S. S., Sharma, K., & Sethi, K. C. (2024). Development of time–cost trade-off optimization model for construction projects with MOPSO technique. Asian Journal of Civil Engineering, 0123456789. https://doi.org/10.1007/s42107-024-01063-3

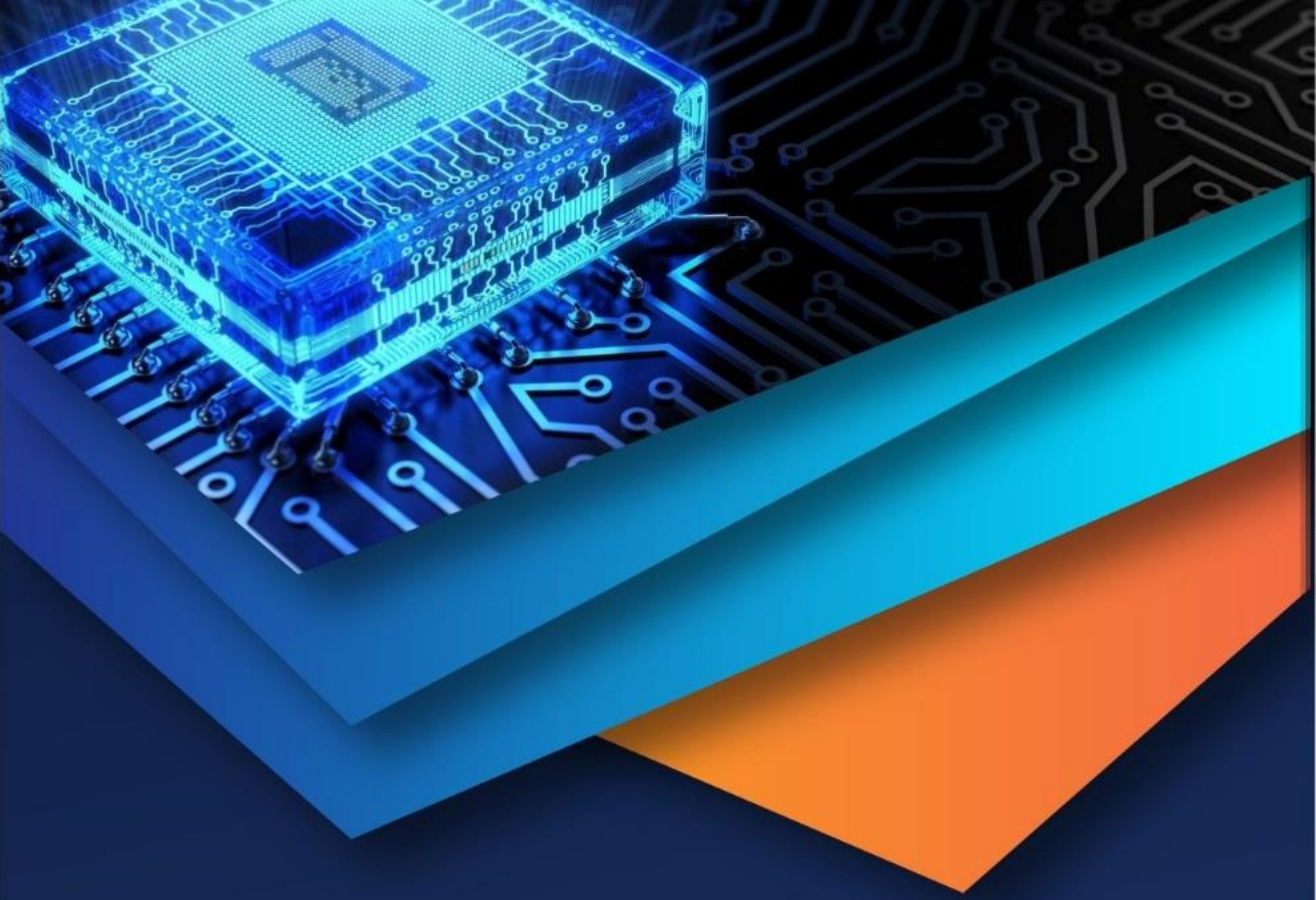
[2] Behera, A. P., Dhawan, A., Rathinakumar, V., Bharadwaj, M., Rajput, J. S., & Sethi, K. C. (2024). Optimizing time, cost, environmental impact, and client satisfaction in sustainable construction projects using LHS-NSGA-III: a multi-objective approach. Asian Journal of Civil Engineering, 0123456789. https://doi.org/10.1007/s42107-024-01221-7

[3] Kaveh, A., Bakhshpoori, T., & Hamze-Ziabari, S. M. (2018). M5' and mars based prediction models for properties of selfcompacting concrete containing fly ash. Periodica Polytechnica Civil Engineering, 62(2), 281–294. https://doi.org/10.3311/PPci.10799

[4] Li, M., & Wu, G. (2014). Robust optimization for time-cost tradeoff problem in construction projects. Abstract and Applied Analysis. https://doi.org/10.1155/2014/926913

[5] Prasad, A., Mayank, B., Gaurav, C., Prachi, S., & Jyoti, S. (2024). Optimizing trade - off between time , cost , and carbon emissions in construction using NSGA - III : an integrated approach for sustainable development. Asian Journal of Civil Engineering. https://doi.org/10.1007/s42107-024-01176-9

[6] Sethi, K. C., Rathinakumar, V., Harishankar, S., Bhadoriya, G., & Pati, A. K. (2024). Development of discrete opposition-based NSGA-III model for optimizing trade-off between discrete time, cost, and resource in construction projects. Asian Journal of Civil Engineering. https://doi.org/10.1007/s42107-024-01069-x



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