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A TLBO-Based Approach for Optimizing Time, Cost, Energy and Risk in Bridge Construction under the Integrated Project Delivery Model

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Abstract: Traditional optimization approaches in construction management often focus solely on time-cost trade-offs, overlooking sustainability and safety objectives that are increasingly critical in contemporary infrastructure development. This study addresses this gap by formulating a discrete-time multi-objective optimization framework tailored specifically for bridge construction under the Integrated Project Delivery (IPD) model. 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 (standard, accelerated, eco-friendly).

Keywords: Teaching-Learning-Based Optimization (TLBO); MOTLBO; Time-cost-energy-risk trade-off; Integrated Project Delivery (IPD); Pareto optimality; Construction risk; Sustainable infrastructure.

I. INTRODUCTION

The construction industry is key to a nation's growth and development. Among the various forms of infrastructure, bridge construction is particularly critical due to its role in enabling mobility, connectivity, and regional integration. However, bridge projects are inherently complex, involving a multitude of interdependent activities, fluctuating resource constraints, safety risks, and growing sustainability requirements. Traditionally, the primary focus in construction project management has been on minimizing project duration and cost, often side lining other vital parameters such as energy consumption and risk exposure. This limited scope of optimization strategies leads to sub-optimal project outcomes in terms of environmental sustainability, safety, and long-term operational efficiency. Heightened global awareness of sustainable development, energy optimization, and risk control has driven a strategic reorientation in construction project methodologies. Bridge construction, characterized by its intensive resource use and elevated risk profile, has become a critical focus for the deployment of multi-objective optimization (MOO) strategies.

This research focuses on optimizing a reinforced concrete girder bridge construction project, which is both resource-intensive and strategically vital for regional transportation. The project is modeled with twelve core activities, each having three execution modes: standard, accelerated, and eco-friendly. These modes represent varying trade-offs in duration, cost, energy use, and risk. For instance, accelerated modes reduce project duration but increase energy consumption and risk, while eco-friendly modes lower environmental impact but extend timelines. By analyzing and optimizing these trade-offs using the MOTLBO algorithm, this study generates a Pareto front of optimal solutions, enabling informed decision-making aligned with project priorities.

II. RESEARCH OBJECTIVES

The present study aims to address the limitations of traditional construction optimization models by developing a comprehensive multi-objective framework tailored for bridge construction projects. The specific research objectives are:

1) To apply the proposed MOTLBO-based optimization framework to a real-world reinforced concrete girder bridge project and generate Pareto-optimal trade-off solutions.
2) 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.

III. LITERATURE REVIEW

Construction projects are inherently complex and multidisciplinary, involving the coordination of various resources, stakeholders, and interdependent activities. The successful execution of such projects demands the achievement of multiple objectives that are often conflicting in nature—such as minimizing project duration and cost while maximizing safety, sustainability, and quality. These challenges have led to the increasing adoption of multi-objective optimization (MOO) techniques in construction management, particularly in the areas of project scheduling, resource allocation, and performance trade-off analysis.

The conventional optimization techniques, such as linear programming, dynamic programming, and critical path methods (CPM), are often insufficient to handle the nonlinear, dynamic, and discrete nature of real-world construction problems. As a result, metaheuristic algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), and more recently, Teaching-Learning-Based Optimization (TLBO) and its multi-objective variant (MOTLBO) have gained popularity due to their adaptability, scalability, and ability to avoid local optima. Recent advancements in computational power and optimization theory have enabled the application of hybrid and adaptive MOO algorithms that outperform traditional methods in both speed and solution diversity. For example, the Multi-Objective Teaching-Learning-Based Optimization (MOTLBO) algorithm mimics the classroom learning process and has shown superior performance in solving discrete scheduling problems in construction. It offers faster convergence, better exploration of the solution space, and fewer algorithmic parameters to tune compared to its counterparts like NSGA-II or MOPSO. In conclusion, multi-objective optimization represents a paradigm shift in construction project management, offering a structured and computationally effective approach to resolving complex trade-offs. Its integration into project planning, especially under collaborative frameworks like IPD, can significantly enhance decision-making by aligning project execution with economic, environmental, and safety goals. The growing body of literature and successful case applications affirm the relevance of MOO as an indispensable tool for sustainable and efficient construction planning.

1) *Time-Cost Optimization Models in Construction*

The construction industry is constantly challenged to deliver projects within a specified time frame and budget. However, these two objectives—time and cost—are often in conflict.

2) *Traditional Time-Cost Models*

To overcome the limitations of deterministic models, researchers began applying heuristic and metaheuristic algorithms that simulate natural and social processes for global optimization. Among these, Genetic Algorithms (GA), Ant Colony Optimization (ACO), and Particle Swarm Optimization (PSO) have been widely adopted for solving TCTO problems. These algorithms allow for flexible modeling of non-linear and multi-modal objective functions and can incorporate project constraints more realistically. For instance, PSO-based models can identify multiple time-cost combinations by simulating a swarm of solutions that iteratively adjust based on personal and global best positions.

Multi-Objective Evolutionary Algorithms (MOEAs) like NSGA-II and NSGA-III have further improved time-cost optimization by generating Pareto fronts, which provide multiple non-dominated solutions for decision-makers. These models offer valuable trade-off insights rather than a single optimal solution, thereby facilitating better stakeholder negotiation and risk management. For example, an NSGA-II-based model could help a project manager choose between a fast-track solution with higher cost and an economical solution with extended duration.

In IPD-driven environments, TCTO optimization is not limited to internal project logistics but also includes external considerations such as contract penalties, material procurement delays, and stakeholder preferences. As a result, TCTO models must be adaptive, transparent, and capable of integrating diverse constraints into a single decision-support system.

3) *Recent Advances and Hybrid Optimization*

Recent advancements in construction optimization include hybrid models that combine metaheuristics with machine learning, fuzzy logic, and simulation-based approaches. For example, hybrid PSO-GA models have been used to enhance solution diversity and convergence accuracy in large-scale infrastructure projects. Similarly, Fuzzy MOGA models incorporate uncertainty into time and cost estimates, thereby reflecting the real-world ambiguity faced in construction planning.

Moreover, algorithms like Multi-Objective Teaching-Learning-Based Optimization (MOTLBO) have emerged as promising alternatives due to their simple structure, minimal parameter tuning, and strong performance in handling discrete decision variables. MOTLBO mimics the teaching and peer-learning processes and has shown effectiveness in resolving complex trade-offs in construction project scheduling.

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IV. PROPOSED METHOD

The MOTLBO algorithm is an enhanced version of TLBO that mimics the knowledge transfer process in a classroom to solve complex optimization problems. It consists of two key phases: the Teacher Phase, where the best-performing individual (teacher) influences the rest of the population (students) to improve overall learning, and the Learner Phase, where individuals interact and learn from each other to refine their solutions iteratively. It consists of following steps;

1) Step 1) Problem Initialization: The first step is to define the project's activities, modes of execution, and restrictions, as shown in Equations (1) to (4).
2) Step 2) Population Initialization: The optimization process begins with defining project activities, execution modes, and dependencies while establishing objective functions to minimize time, cost, energy, and risk. Key constraints such as budget limits, project schedule, precedence relationships, and resource availability are set to ensure feasibility. Decision variables are initialized, where each activity is assigned multiple execution modes with predefined parameters, forming the foundation for the optimization framework.
3) Step 3) Teacher Phase (Guided Learning Process): In this phase, the best-performing individual is designated as teacher, guiding the rest of population toward better solutions. The teacher influences the learning process by adjusting the students' (solutions') positions using the Equation (4.1):

$$X' = X + r \times (X_{best} - T \times X_{mean}) \tag{4.1}$$

Where, r is a random number, X_{best} is the best solution, X_{mean} is the mean population solution, and T is the teaching factor.

4) Step 4) Learner Phase (Peer-to-Peer Learning): During the learner phase, individual engage with each other and share information. After comparing two solution pairs, the weaker solution is modified using the following criteria:

$$X_i' = X_i + r \times (X_j - X_i) \quad if \;\; f(X_j) < f(X_i) \tag{4.2}$$

Where, $f(X)$ is the evaluation of the objective function and X_i and X_j are two randomly chosen solutions.

5) Step 5) Non-Dominated Sorting and Pareto Front Generation: The updated population is ranked using non-dominated sorting to identify optimal trade-off solutions. Crowding distance is used to maintain diversity among solutions on the Pareto front, ensuring a well-distributed set of optimal alternatives.
6) Step 6) Termination and Solution Selection: The algorithm proceeds iteratively until a predefined number of iterations is reached or convergence is achieved. The final Pareto front offers multiple trade-off solutions. The most appropriate solution is selected using decision-support tools such as the Weighted Sum Method (WSM), depending on stakeholder preferences.

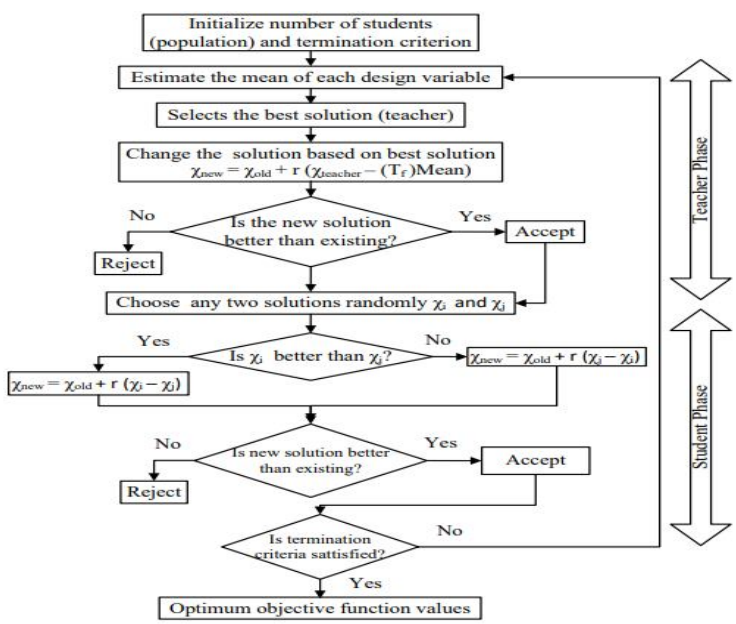

Figure 4.1. Workflow of MOTLBO Framework

V. BRIDGE CONSTRUCTION PROJECT

A. Bridge Project Overview

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.

Table 5.1. Key Bridge Specifications

Parameter	Details
Bridge Type	Reinforced Concrete Girder Bridge
Length	300 meters
Width	12 meters
Span Configuration	6 spans, each 50 meters
Deck Material	Reinforced Concrete
Foundation Type	Pile Foundation
Pier Type	Reinforced Concrete
Abutments	Reinforced Concrete
Pavement	Asphalt Overlay
Design Life	100 years
Traffic Load Capacity	Class 70R (IRC Standards)
Sustainability Features	Eco-friendly materials, reduced emissions
Estimated Budget	INR 4.5 Crores
Project Timeline	18 months

B. Activity Modeling and Input Data

The bridge construction process is divided into twelve key activities, each with multiple execution modes, allowing for flexible decision-making based on time, cost, energy consumption, and risk considerations (Table 5.2). Each activity presents a unique trade-off between time, cost, energy, and risk, making multi-objective optimization essential for determining the most balanced execution strategy. By systematically evaluating these execution modes, 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

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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 3D trade-off plots (Figures 6.1 to 6.3) provide a holistic view of the interdependencies among multiple objectives.

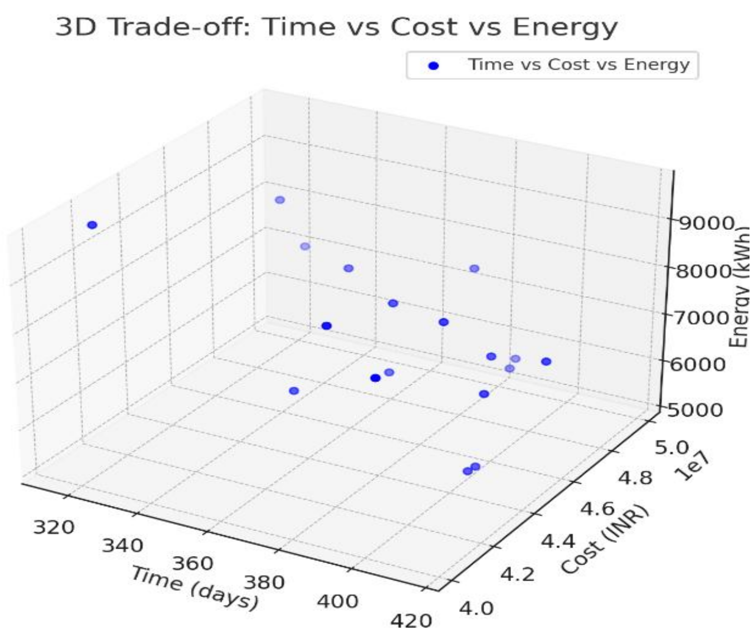

Figure 6.1. Time-Cost-Energy Trade-Off

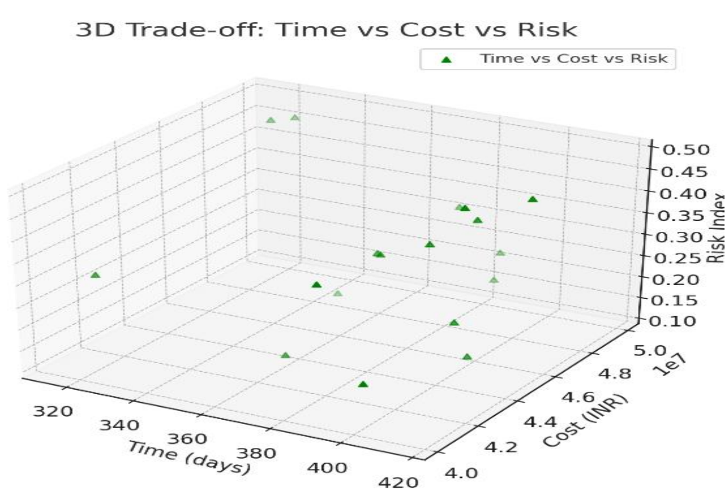

Figure 6.2. Time-Cost-Risk Trade-Off

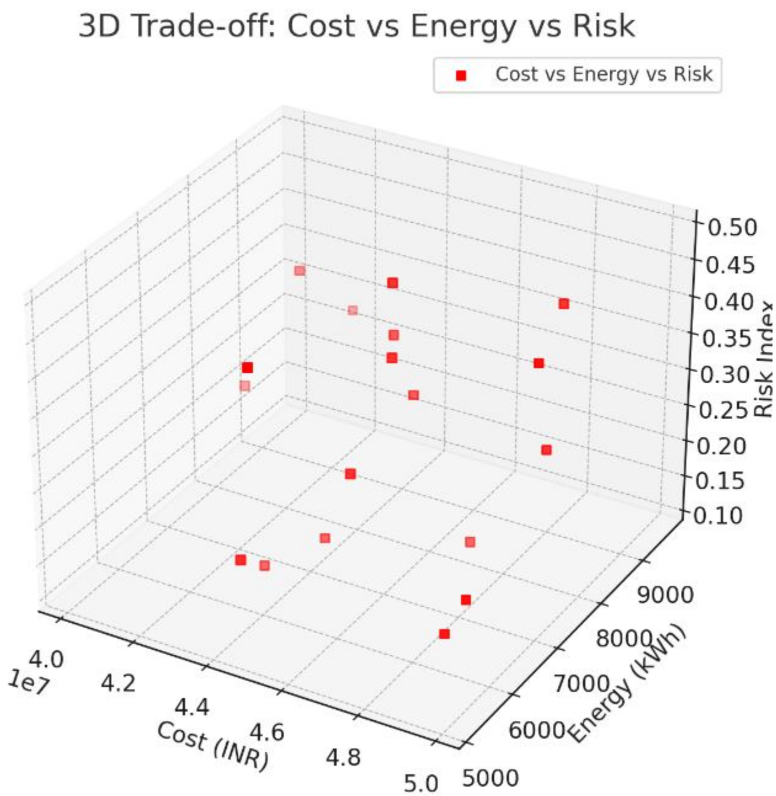

Figure 6.3. Cost-Energy-Risk Trade-Off

VII. CONCLUSIONS

The research focused on developing a robust multi-objective optimization framework to address the multifaceted challenges encountered in bridge construction projects, particularly under the Integrated Project Delivery (IPD) framework. Using the Multi-Objective Teaching-Learning-Based Optimization (MOTLBO) algorithm, the study simultaneously optimized time, cost, energy consumption, and risk—four critical yet often conflicting objectives. The chapter outlines the achievement of these objectives, provides conclusive answers to the research questions, summarizes the findings, and offers final reflections along with directions for future research.

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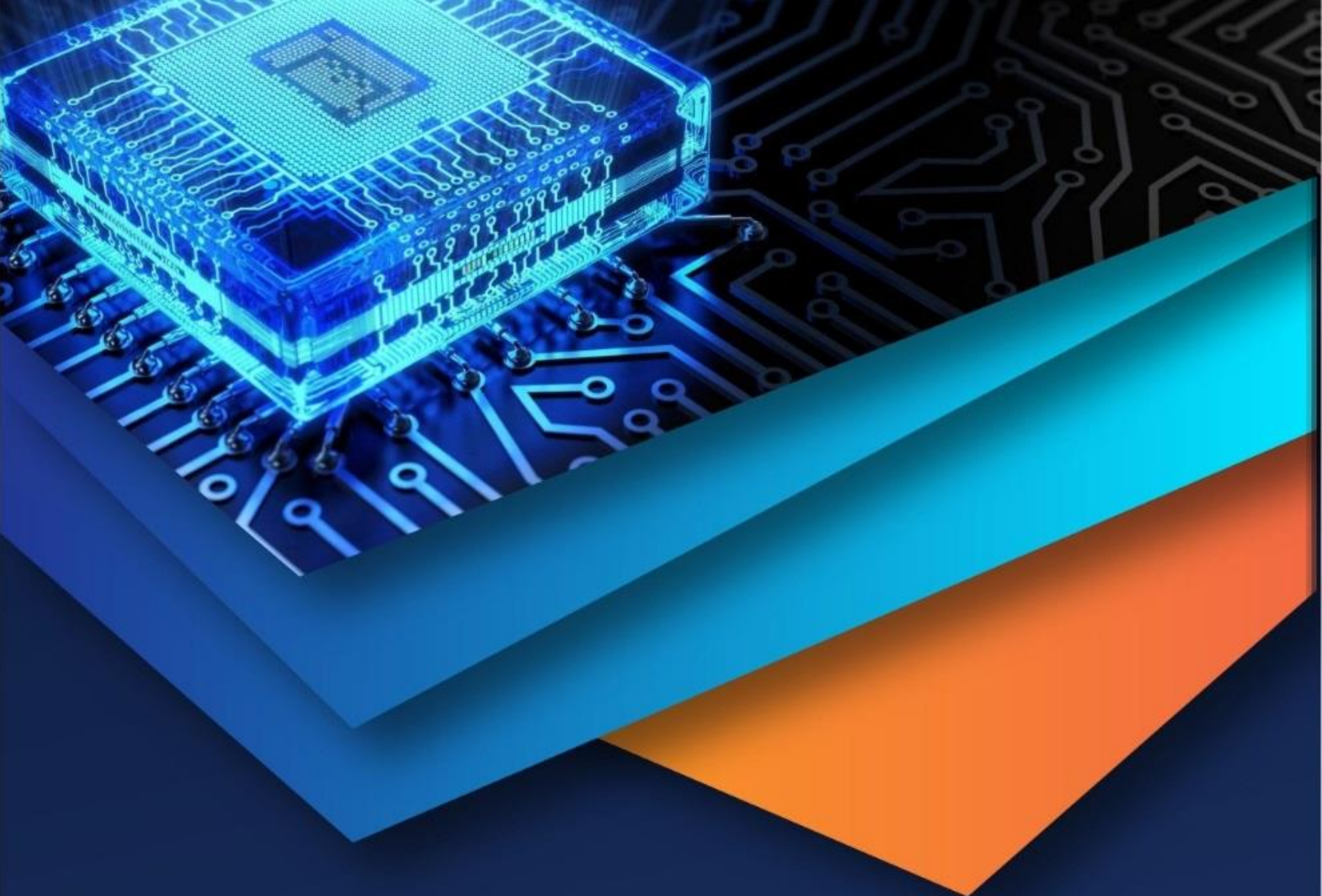

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