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Opposition-Based NSGA-III Framework for Multi-Objective Optimization of Retrofitting Projects: Balancing Time, Cost, Quality, Energy, Safety, and Environmental Impact

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Abstract: ***The study highlights significant theoretical and practical contributions, including the incorporation of safety and environmental impact—often neglected in previous models—and the demonstration of adaptability across varied urban contexts. Limitations such as computational intensity and generalizability are acknowledged, with future research directions suggested in areas like dynamic modeling, stakeholder integration, and AI-enhanced decision-making.***
Keywords: Urban Infrastructure Retrofitting; Multi-Objective Optimization; NSGA-III Algorithm; Opposition-Based Learning (OBL); Sustainable Construction Management.

I. INTRODUCTION

This research has proposed hybrid models that enhance the search and initialization mechanisms of traditional algorithms. One such advancement is the integration of Opposition-Based Learning (OBL) with NSGA-III, resulting in the Opposition-Based NSGA-III (OBNSGA-III) framework. Opposition-based learning was first introduced by Tizhoosh (2005) as a strategy to improve the diversity of the search population by simultaneously evaluating candidate solutions and their opposite counterparts.

II. RESEARCH OBJECTIVES

1) To develop a comprehensive mathematical formulation for the six objectives in retrofitting—minimizing completion time (CTRP), minimizing completion cost (CCRP), maximizing quality index (QIRP), minimizing energy consumption (ECRP), minimizing safety risk (SRRP), and minimizing environmental impact (EIRP).
2) To enhance the Non-Dominated Sorting Genetic Algorithm III (NSGA-III) using Opposition-Based Learning (OBL) to improve initial population diversity, exploration capacity, and convergence performance.
3) To construct and validate a real-world case study, involving a commercial retrofitting project in Delhi-NCR, with multiple aspects and options characterized by quantified performance metrics.
4) To generate a diverse Pareto-optimal front representing trade-offs among the six TCQESET objectives, allowing decision-makers to evaluate multiple retrofitting strategies.
5) To compare the performance of the proposed OBNSGA-III model with benchmark algorithms such as standard NSGA-III, MOPSO, and OB-MODE using metrics like Generational Distance (GD), Spacing Metric (SM), Hypervolume (HV), Quality Metric (QM), and Computational Time (CT).
6) To recommend the most balanced retrofitting solution using a weighted sum approach and provide insights into practical applications of the framework in sustainable infrastructure planning.

III. LITERATURE REVIEW

Multi-objective optimization in construction management has shifted from theoretical interest to practical necessity, particularly in the era of sustainable and resilient infrastructure development. The use of advanced evolutionary algorithms—especially NSGA-III and its hybridizations—has enabled optimization across multiple performance dimensions. As demonstrated in this research through the proposed OBNSGA-III model, MOO is a powerful paradigm that facilitates intelligent decision-making and strategic trade-offs in complex retrofitting scenarios.

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IV. RESEARCH METHODOLOGY

The TCQESET model for retrofitting projects is developed using time, cost, quality, energy consumption, safety, and environmental impact of retrofitting aspects as inputs. Consider a retrofitting project with *n*-aspects (A_1, A_2,…..A_n), where each of the m possible retrofitting options (O_1, O_2,…..O_m) can be used to perform a different aspect of the project. The distinct set of resources (RS_1, RS_2,….RS_m) that control the values of time, cost, quality, energy consumption, safety, and environmental impact of activities characterises each retrofitting option in this case. This study seeks to simultaneously optimize the following aspects of retrofitting projects: completion time of retrofitting project (CTRP), completion cost of retrofitting project (CCRP), quality index of retrofitting project (QIRP), safety risk of retrofitting project (SRRP), energy consumption of retrofitting project (ECRP), and environmental impact of retrofitting project (EIRP). Additionally, the following are crucial presumptions for the creation of the TCQESET model: (1) Retrofitting aspects must adhere to their precedence relationships; (2) resources are available in finite and discrete quantities; (3) decision variables are non-zero positive integers constrained by lower and upper limits; and (4) each retrofitting component must be executed through a singular, continuous retrofitting option to ensure successful project completion. The flow chart for proposed scheduling model is presented as Figure 3.3

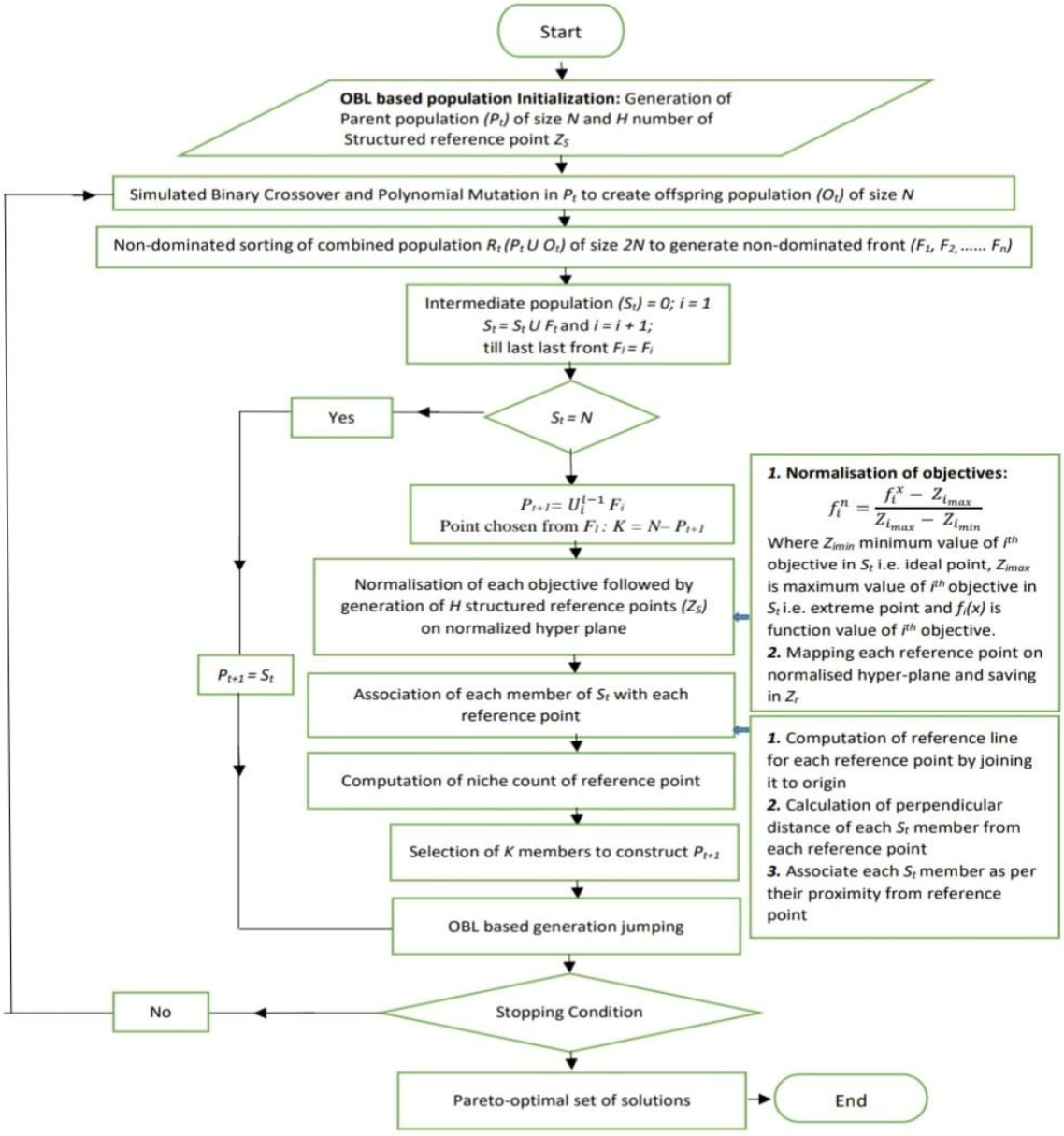


Figure 3.3 Flow chart for OBNSGA III

V. RESULTS AND DISCUSSION

Table 4.1 presents the comprehensive dataset used to validate the proposed TCQESET optimization model for retrofitting projects using OBNSGA III algorithm. The case study focuses on a 20-year-old commercial building located in Delhi-NCR, India, with a built-up area of 5,000 square meters.

Table 4.1 Case Study Data

Aspect	Option	Time (Days)	Cost (INR)	Quality Score	Energy Consumption (kWh)	Safety Score	Environmental Impact (kg CO_2-eq.)
A1) Structural Reinforcement	1-Steel frame reinforcement	5	207504	0.852	200	3.911	1.202
	2-Concrete jacketing	7	186753	0.804	180	4.812	1.301
	3-Carbon fiber wrapping	8	249033	0.906	150	2.882	1.151
A2) Energy Efficiency Enhancement	1-Energy-efficient HVAC system	4	166012	0.883	120	4.873	1.101
	2-Insulation upgrades	2	145252	0.824	100	3.833	1.503
	3-LED lighting	1	124544	0.785	50	4.801	0.302
A3) Safety Enhancements	1-Fire protection systems	7	269767	0.922	170	3.952	1.002
	2-Seismic retrofitting	8	290532	0.954	200	4.963	1.501
	3-Emergency lighting	4	166012	0.852	140	4.894	1.123
A4) Aesthetic Enhancements	1-Facade redesign	5	228211	0.875	130	4.855	2.253
	2-Landscaping	4	186723	0.838	110	3.827	1.151
	3-Art installations	2	145212	0.792	90	2.781	1.108
A5) Environmental Impact Reduction	1-Low-carbon materials	3	132869	0.804	80	4.815	0.605
	2-Waste recycling program	4	116223	0.782	70	3.808	0.401
	3-Rainwater harvesting	5	186733	0.829	100	4.833	1.120
A6) Project Quality Improvements	1-Advanced monitoring system	4	249089	0.905	90	4.922	0.701
	2-High-durability materials	5	207512	0.883	95	3.906	0.503
	3-Automated quality control	6	228233	0.912	85	4.947	0.651
A7) Smart Building Integration	1-Building automation	4	186709	0.854	120	3.862	1.120
	2-Energy management software	3	166093	0.845	100	4.885	1.101
	3-Smart building sensors	4	207560	0.861	90	3.877	0.907
A8) Water Efficiency Measures	1-Low-flow fixtures	2	124525	0.800	60	4.803	0.604
	2-Greywater recycling	4	166061	0.858	75	4.852	0.753
	3-Rainwater harvesting	5	207553	0.888	95	4.867	0.956
A9) Waste Management Strategies	1-Construction waste recycling	2	103744	0.753	50	3.755	0.502
	2-Salvaging materials	4	145233	0.806	65	4.782	0.653
	3-Sustainable construction practices	5	186712	0.855	80	3.804	0.804
A10) Health and Well-being	1-Ventilation upgrades	4	166081	0.906	70	4.883	0.707
	2-Air filtration systems	2	145241	0.875	60	4.862	0.604
	3-Access to natural light	1	124572	0.857	50	4.893	0.501
A11) Community Engagement Initiatives	1-Public outreach programs	2	83003	0.828	45	4.836	0.452
	2-Stakeholder workshops	4	103722	0.864	55	3.857	0.551
	3-Participatory design processes	5	124573	0.895	60	2.909	0.602

Table 4.3 presents Pareto-optimal solutions generated by OBNSGA III algorithm for retrofitting case study project in Delhi-NCR. A total of 22 non-dominated solutions were obtained, each offering a distinct combination of retrofitting options across the eleven aspects considered in the model. These solutions reflect optimal trade-offs among six critical objectives.

Table 4.3 Pareto-Optimal Solutions

Solution ID	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	Project Time (days)	Project Cost (INR)	Project Quality Index	Energy Consumption (kWh)	Safety Risk Score	Environmental Impact (kg CO2-eq)
S1	1	3	2	2	3	3	2	3	1	2	3	60	1205817	0.899	1132	1.34	0.696
S2	2	3	1	3	1	3	2	1	1	2	1	87	2063722	0.939	1690	4.16	0.82
S3	2	2	3	3	3	2	1	2	2	3	1	62	2812492	0.814	1220	3.1	2.492
S4	3	2	2	1	1	3	1	2	3	3	2	83	2588974	0.84	1312	2.92	1.193
S5	1	2	1	2	3	1	3	3	1	1	2	51	1695209	0.883	509	3.24	0.599
S6	2	1	3	1	1	1	3	2	3	2	2	60	3443624	0.93	1382	1.17	1.308
S7	3	1	3	3	2	2	3	3	2	1	3	62	3326575	0.923	653	1.78	2.354
S8	1	2	2	2	2	3	1	2	1	2	2	50	4424312	0.878	575	3.91	2.478
S9	3	2	3	1	1	3	1	3	1	1	3	95	3265261	0.794	627	1.61	1.687
S10	2	1	1	2	1	2	2	2	2	1	3	72	2811435	0.906	1060	2.58	0.79
S11	3	1	3	1	1	2	3	1	1	2	2	96	2816776	0.934	1718	3.56	1.151
S12	1	3	3	3	3	3	1	2	2	1	1	81	3177193	0.919	740	3.41	1.474
S13	3	2	3	2	2	1	1	2	2	1	1	71	2172884	0.836	1997	4.11	1.161
S14	3	2	3	2	3	2	2	1	2	2	1	78	2038992	0.785	1165	3.94	0.571
S15	1	1	1	3	2	1	1	2	1	3	3	59	1095471	0.876	1883	1.67	1.813
S16	2	2	1	3	3	3	1	2	3	1	1	80	2951635	0.774	1766	4.99	1.365
S17	3	3	3	2	3	2	1	2	3	1	3	96	1554860	0.924	1441	3.91	1.236
S18	3	1	1	1	3	1	1	2	1	3	1	94	3392969	0.792	1857	2.03	2.059
S19	1	1	1	2	3	2	2	2	2	2	3	87	3116989	0.793	1363	4.64	1.116
S20	1	1	3	2	2	1	2	1	2	1	2	79	2840863	0.923	1812	1.67	0.588
S21	1	1	1	1	2	2	3	2	1	1	3	70	3592810	0.822	771	1.54	0.5
S22	3	2	1	2	1	2	3	3	3	3	1	56	1077529	0.799	578	1.66	1.5
Mean												74.05	2612108	0.86	1238.68	2.86	1.32
Standard Deviation												14.99	893404	0.06	494.64	1.20	0.62

The study employs a weighted sum technique, enabling the selection of a solution using the following equations:

$$Min \sqrt{\sum_{j=1}^{n} \sum_{i=1}^{m} w_i x_{ij}}$$

s.to $\sum_{i=1}^{m} w_i = 1$

To gain deeper insights into the nature of trade-offs between multiple objectives in the retrofitting project, various two-dimensional are presented in Figures.

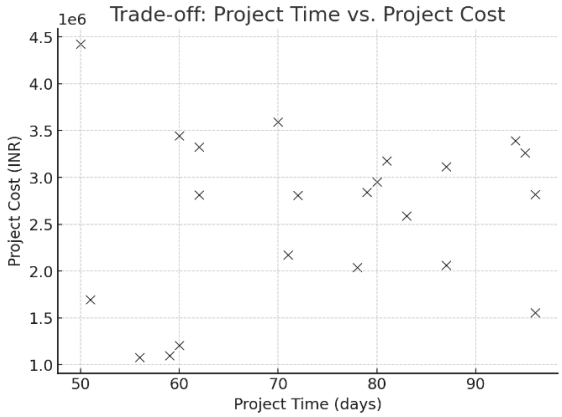


Figure 4.1 Time-Cost Trade-Off

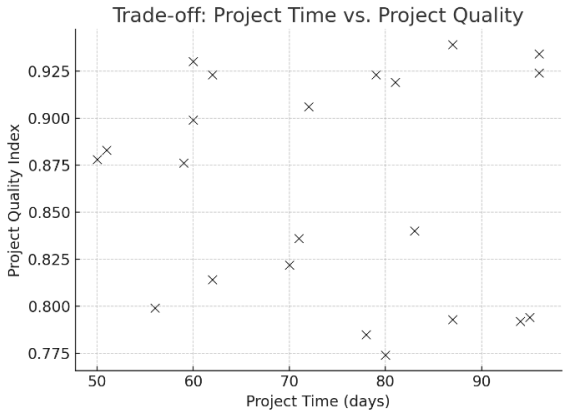


Figure 4.2 Time-Quality Trade-Off

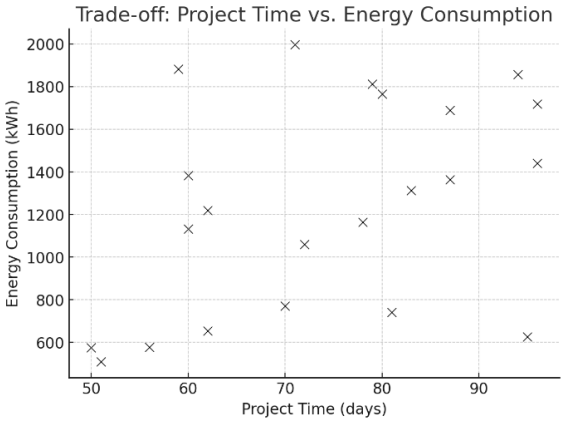


Figure 4.3 Time-Energy Consumption Trade-Off

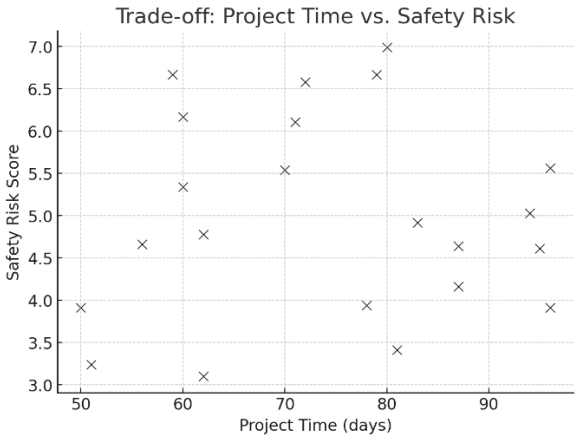


Figure 4.4 Time-Safety Risk Trade-Off

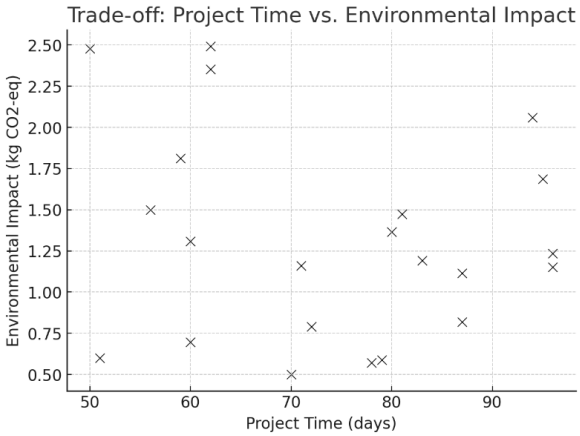


Figure 4.5 Time-Environmental Impact Trade-Off

The findings from this study demonstrate the robustness and efficiency of the proposed OBNSGA III-based TCQESET optimization framework in managing complex retrofitting projects. Among the 22 Pareto-optimal solutions generated for the case study project, each offers a unique balance among the six objectives: time, cost, quality, energy consumption, safety, and environmental impact.

VI. CONCLUSION

This thesis proposed and validated a novel hybrid multi-objective optimization framework for enhancing the performance of urban infrastructure retrofitting projects. This study reaffirms that urban infrastructure retrofitting is inherently a complex, multi-dimensional challenge that cannot be adequately addressed using traditional single- or bi-objective models. By integrating a hybrid NSGA-III–OBL optimization algorithm, this research advances the methodological toolkit for urban planners, offering a solution that is both technically robust and practically viable.

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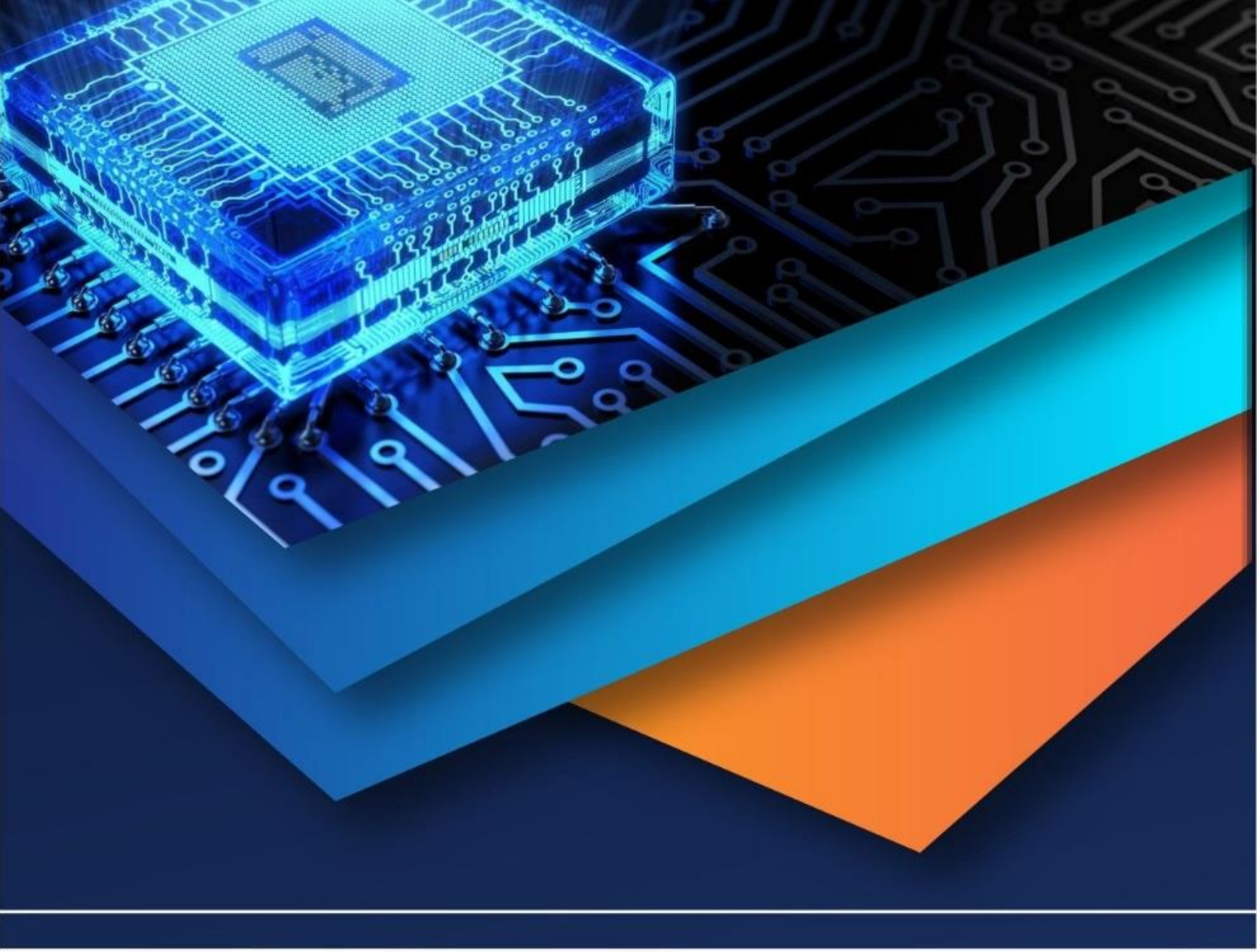
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