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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:*** ***This study presents a hybrid multi-objective optimization framework combining NSGA-III with Opposition-Based Learning (OBL) to improve urban infrastructure retrofitting by optimizing project duration, cost, quality, safety, and carbon emissions.***

***Keywords: Urban Infrastructure Retrofitting; Multi-Objective Optimization; NSGA-III Algorithm; Opposition-Based Learning (OBL); Sustainable Construction Management.***

## I. INTRODUCTION

This research proposes a novel, comprehensive TCQESET optimization framework using an Opposition-Based NSGA-III algorithm, validated through a real-world commercial retrofitting case study in Delhi-NCR. This study aims to demonstrate how multi-objective optimization can help urban planners and construction professionals make data-driven, sustainable, and performance-oriented retrofitting decisions.

## II. OBJECTIVES OF THE STUDY

The primary aim of this research is to develop and validate a multi-objective optimization framework for retrofitting projects that addresses the complex and interrelated performance criteria of Time, Cost, Quality, Energy, Safety, and Environmental Impact (TCQESET). The study is guided by the following specific 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

Opposition-Based Learning offers a powerful enhancement mechanism for evolutionary optimization algorithms, especially within many-objective contexts such as retrofitting, scheduling, and infrastructure renewal.

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By exploring both a candidate and its opposite simultaneously, OBL strengthens diversity and accelerates convergence, making it an attractive technique for complex decision-support frameworks. However, careful calibration of its use parameters, computational cost considerations, and adaptation to problem dimensionality are necessary for effective implementation.

## 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.

### *A. Proposed OBNSGA-III Based TCQESET Model*

To address the complex and multidimensional optimization of retrofitting projects, this study presents a novel TCQESET model using the OBNSGA-III. The model efficiently explores and exploits the solution space to provide optimal trade-offs across six crucial project performance criteria. The flow chart for proposed scheduling model is presented as Figure 3.3

### *B. Validation of Model*

To validate the model that was constructed, a test case utilising the NSGA III-based trade-off of time, cost, resources, and environmental impact (TCRET) is derived from literature previously examined by Panwar & Jha (2019). The TCRET problem consisted of 11 activities with a maximum of four retrofitting options, and the results of this test problem were compared with the generated RMOSM using similar algorithm parameters, including a population size of 100, 200 generations, and a crossover and mutation distribution index of 20.

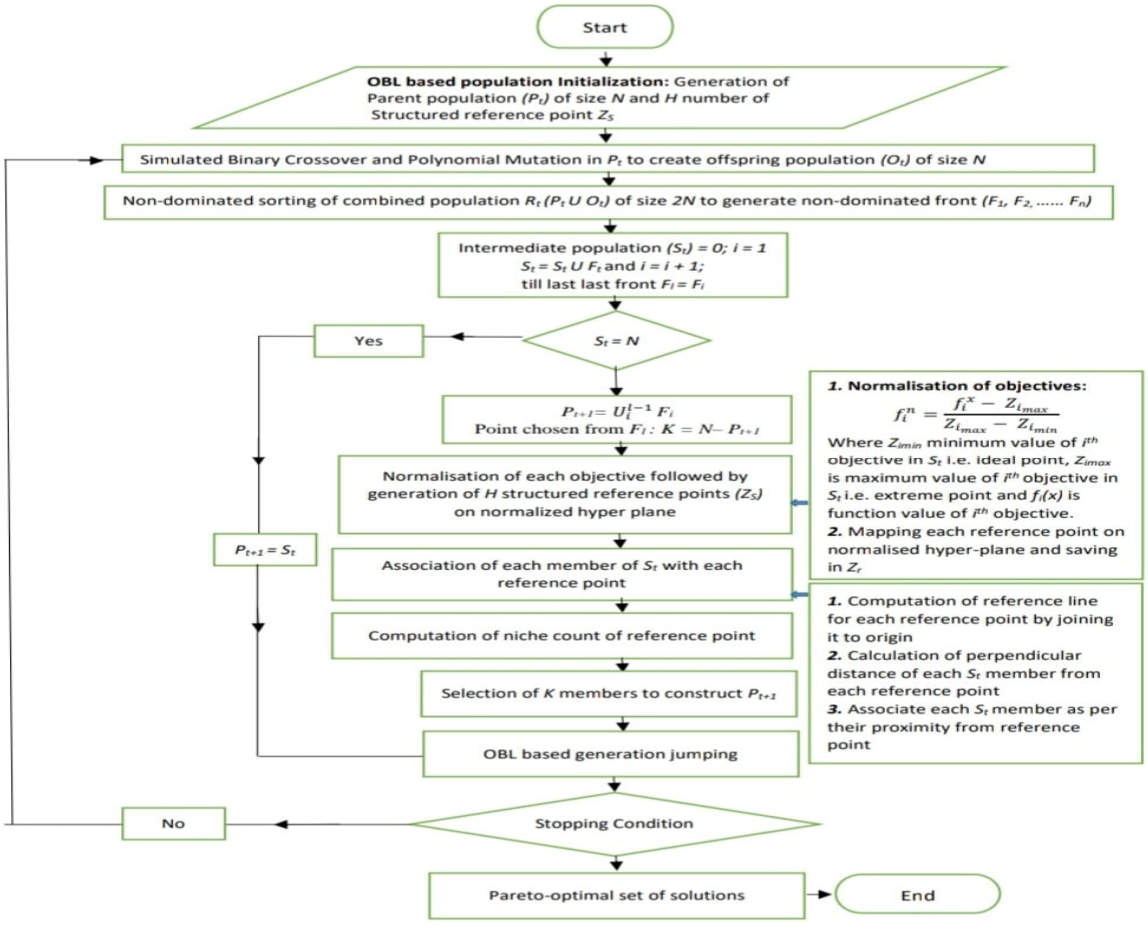



Figure 3.3 Flow chart for OBNSGA III

## V. RESULTS AND DISCUSSION

### A. *Case Study Project*

Table 4.1 presents the comprehensive dataset used to validate the proposed TCQESET optimization model for retrofitting projects using OBNSGA III algorithm.

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 | 3 | 166093 | 0.845 | 100 | 4.885 | 1.101 |

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| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | software | | | | | | | |
| | 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 |

*B. Obtained Results for Case Study Project*

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

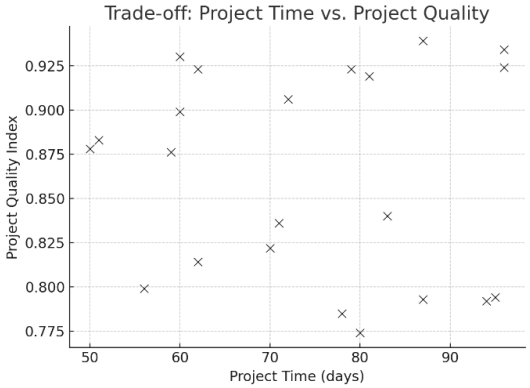
| Solution ID | A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 | A9 | A10 | A11 | Project Time (days) | Project Cost (INR) | Project Quality Index | Energy Consumption (kWh) | Safety Risk Score | Environmental Impact (kg CO2-eq) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S1 | 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 |

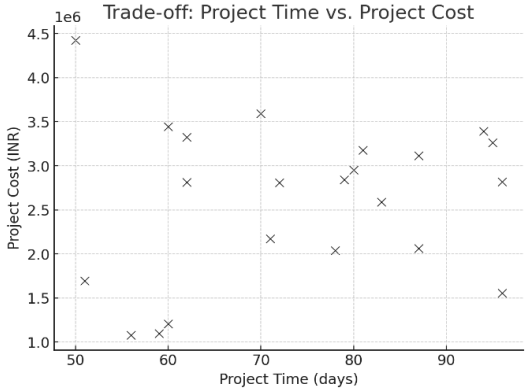
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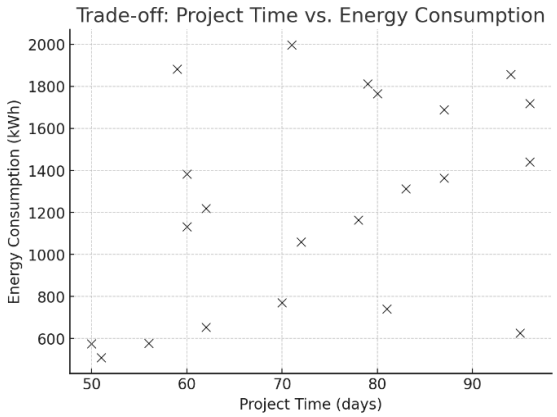
| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S7 | 3 | 1 | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 1 | 3 | 62 | 3326575 | 0.923 | 653 | 1.78 | 2.354 |
| S8 | 1 | 2 | 2 | 2 | 2 | 3 | 1 | 2 | 1 | 2 | 2 | 50 | 4424312 | 0.878 | 575 | 3.91 | 2.478 |
| 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 |

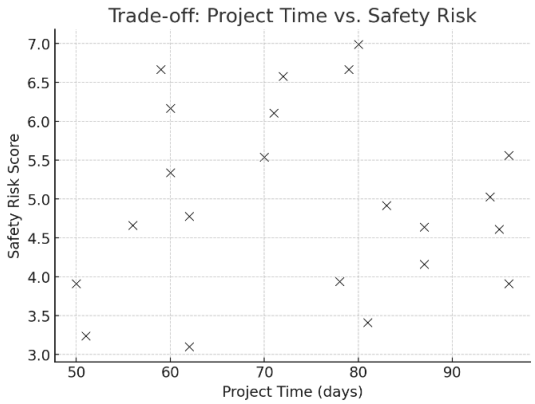
### *C. Analysis of Trade-Off Plots*

To gain deeper insights into the nature of trade-offs between multiple objectives in the retrofitting project, various two-dimensional, three-dimensional, and normalized value path plots were generated and are presented in Figures.






## VI. CONCLUSION

This research proposed and validated a novel hybrid multi-objective optimization framework for enhancing the performance of urban infrastructure retrofitting projects. Recognizing the limitations of traditional Time–Cost–Trade-Off (TCT) models, the study introduced a many-objective formulation integrating five critical performance dimensions: project duration, cost, quality, safety, and carbon emissions.

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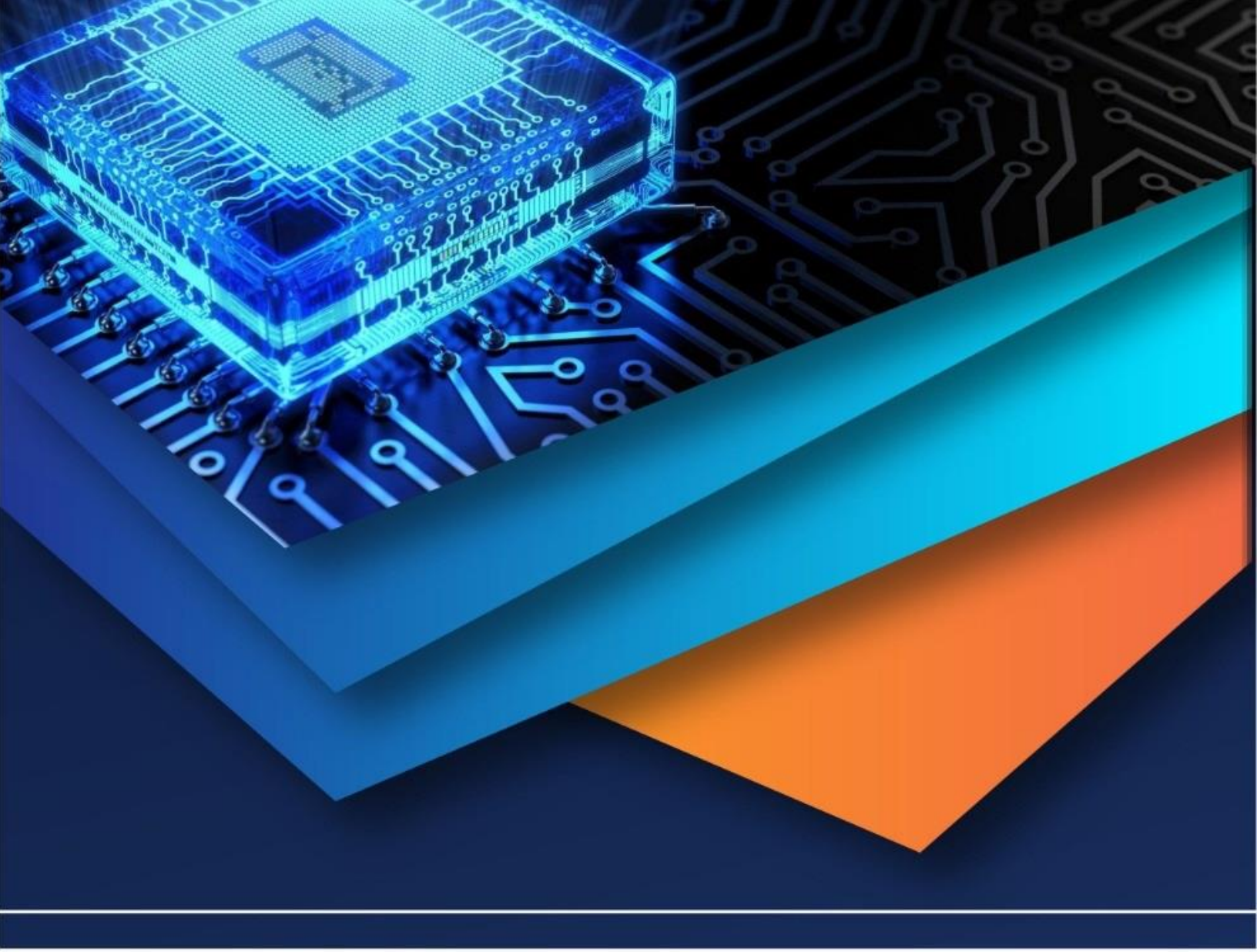
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