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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.

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.

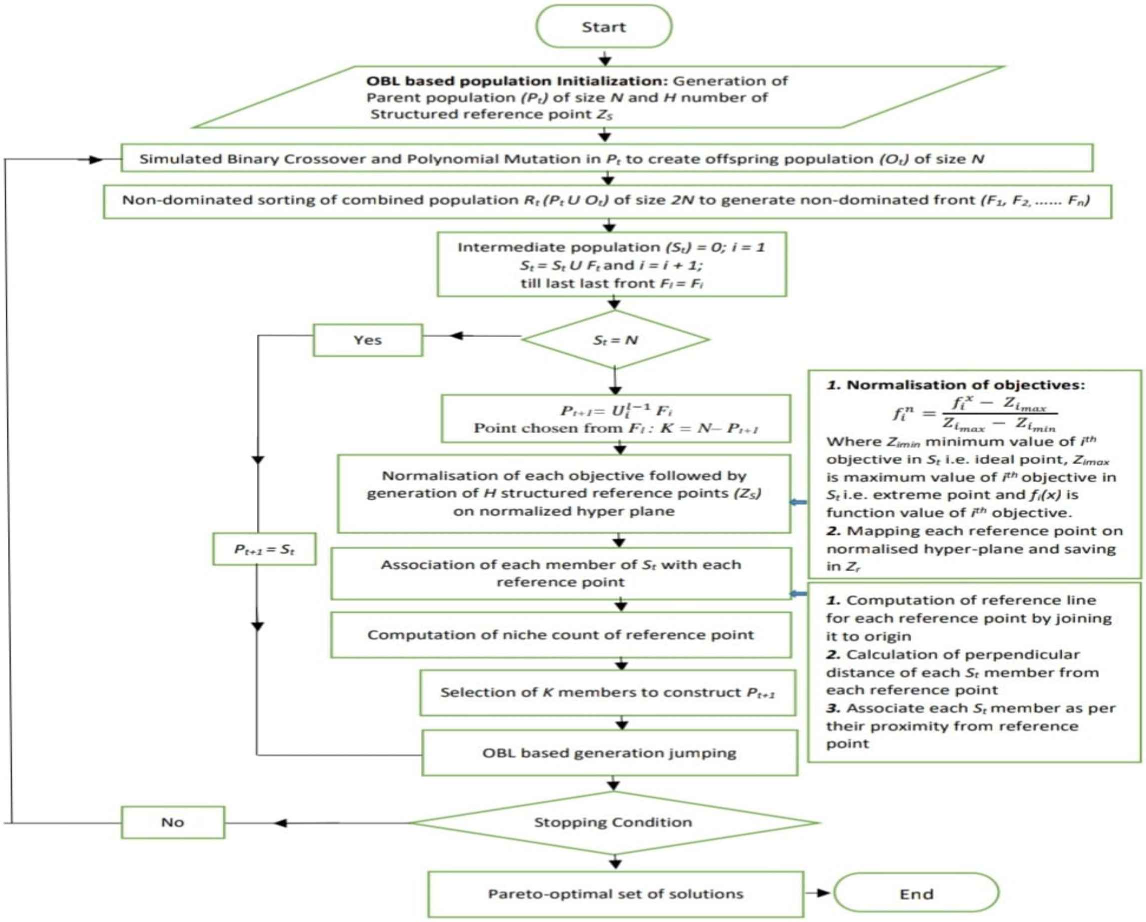


Figure 3.3 Flow chart for OBNSGA III

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

	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.

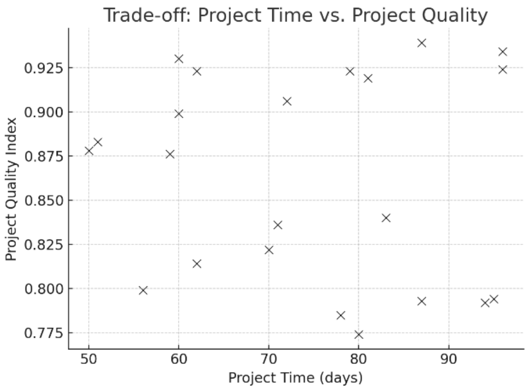
Table 4.3 Pareto-Optimal Solutions

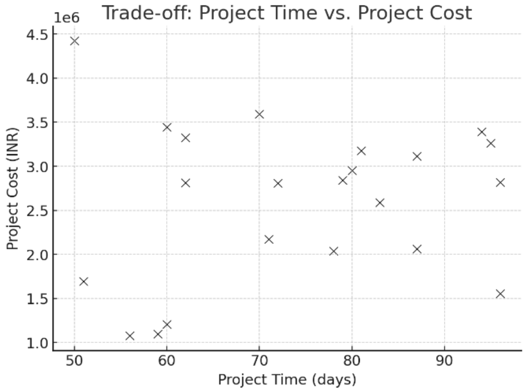
Solution ID	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	Project Time (days)	Project Cost (INR)	Project Quality Index	Energy Consumption (kWh)	Safety Risk Score	Environmental Impact (kg CO2-eq)
S1	1	3	2	2	3	3	2	3	1	2	3	60	1205817	0.899	1132	1.34	0.696
S2	2	3	1	3	1	3	2	1	1	2	1	87	2063722	0.939	1690	4.16	0.82
S3	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

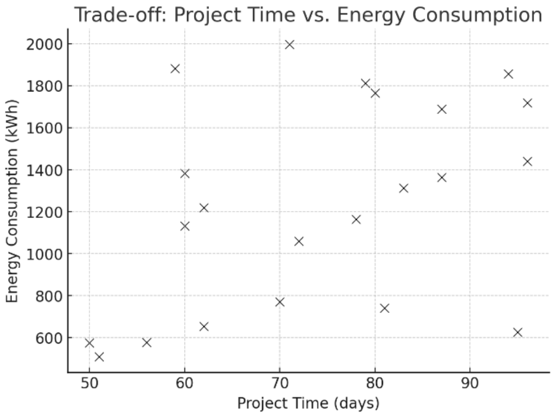
S7	3	1	3	3	2	2	3	3	2	1	3	62	3326575	0.923	653	1.78	2.354
S8	1	2	2	2	2	3	1	2	1	2	2	50	4424312	0.878	575	3.91	2.478
S9	3	2	3	1	1	3	1	3	1	1	3	95	3265261	0.794	627	1.61	1.687
S10	2	1	1	2	1	2	2	2	2	1	3	72	2811435	0.906	1060	2.58	0.79
S11	3	1	3	1	1	2	3	1	1	2	2	96	2816776	0.934	1718	3.56	1.151
S12	1	3	3	3	3	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

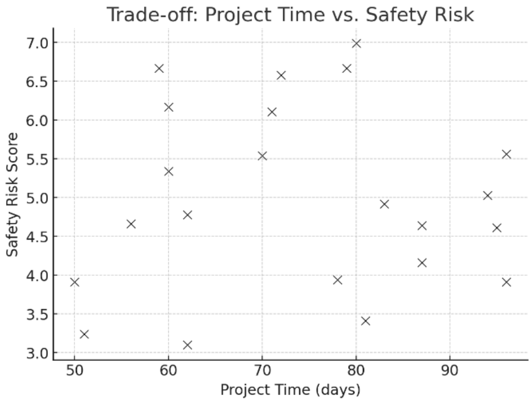
C. *Analysis of Trade-Off Plots*

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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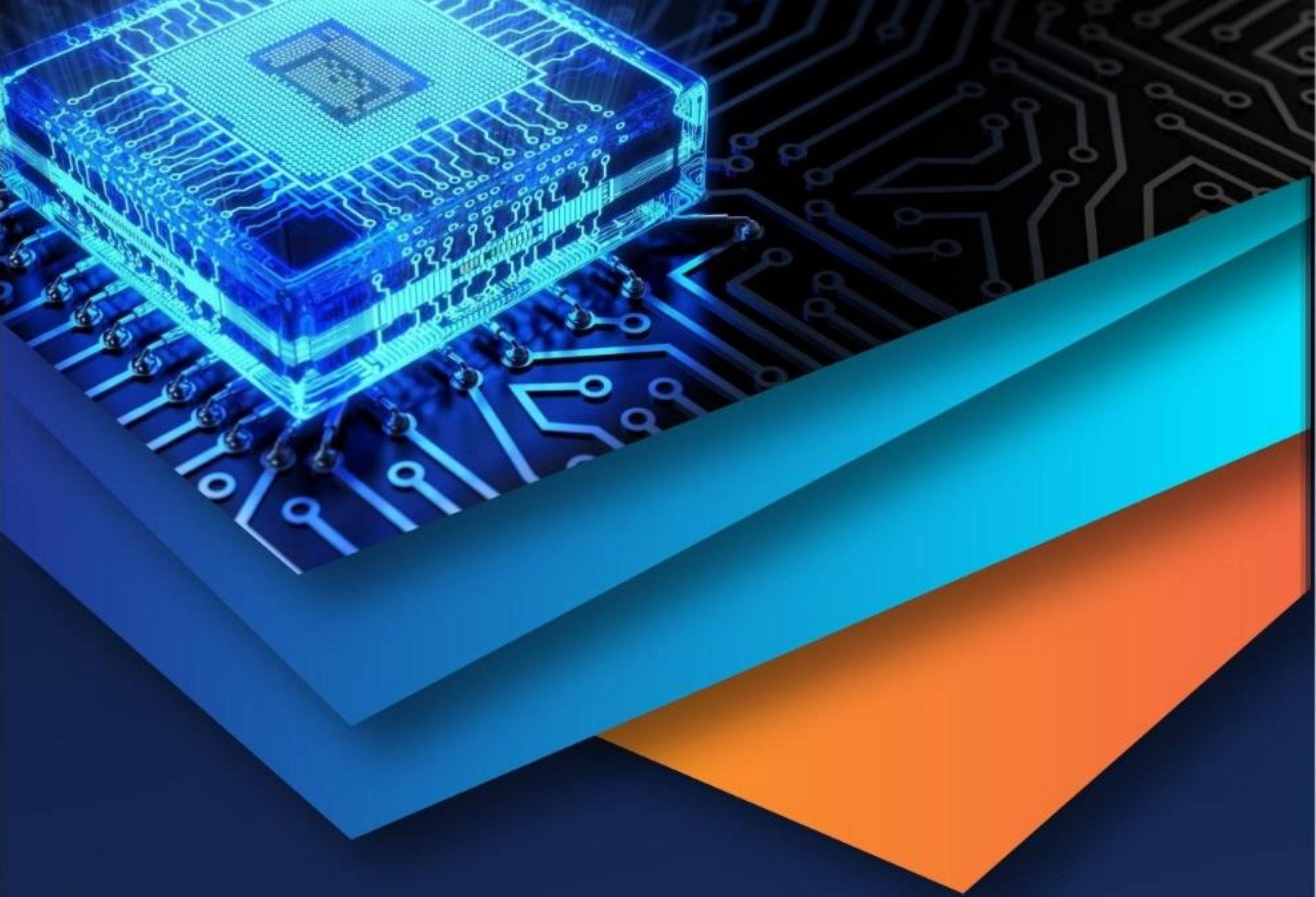

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