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Dynamic Route Optimization for Urban Waste Collection

Mr. Shreyas Bharadhwaj S P[1], Mr. Adithya Sampath[2], Mr. Vishwas A M[3], Ms. Sharanya R Chandra[4], Prof. Krishnan R[5]
Department of Computer Science, Dayananda Sagar College of Engineering

Abstract: Efficient waste collection is a critical aspect of urban management. This paper presents a dynamic route optimization system tailored for garbage collection trucks in urban environments. The proposed approach uses synthetic data generation and vehicle routing algorithms to reduce fuel consumption, minimize travel time, and improve operational efficiency. The solution also includes a dashboard for real-time visualization and analysis of route data. Results show an improvement in efficiency compared to traditional static routing systems. This system can be applied to smart city waste management, enabling proactive decision-making and efficient resource allocation. By integrating real-time traffic data, bin fill levels, and vehicle capacity constraints, the system adapts dynamically to changing conditions in the urban landscape. A reinforcement learning model further enhances the system's ability to predict and prioritize waste collection based on historical patterns. Simulation testing with SUMO demonstrates the model's viability under realistic conditions. The architecture is modular and scalable, making it suitable for deployment across various city infrastructures.
Keywords: Dynamic Routing, Waste Collection, SUMO, Vehicle Routing Problem, Smart City, Optimization, Dashboard, Urban Logistics

I. INTRODUCTION

The rapid pace of urbanization in modern cities has significantly increased the complexity of managing essential civic services, with waste management emerging as one of the most pressing challenges. Traditional waste collection systems rely on static schedules and predefined routes, which often fail to accommodate dynamic urban factors such as fluctuating traffic conditions, inconsistent bin fill levels, and unexpected delays. These limitations lead to increased fuel consumption, higher operational costs, accelerated vehicle wear and tear, and a greater environmental footprint. In response to these inefficiencies, this paper proposes a dynamic routing system for waste collection that leverages real-time analytics, intelligent optimization algorithms, and traffic simulation to deliver smarter and more adaptive logistics.

The system is designed to respond to live data sourced from IoT-enabled smart bins and traffic networks, enabling garbage trucks to dynamically adjust their routes based on current conditions. This intelligent routing framework minimizes redundant travel, balances workloads across fleets, and enhances the system's overall responsiveness. Moreover, it aligns with broader smart city goals by promoting data-driven decision-making, improving transparency in operations, and maximizing resource utilization. To ensure operational viability, the Simulation of Urban Mobility (SUMO) tool is employed to model real-world traffic scenarios and test route performance under varying urban conditions. A centralized dashboard interface supports live monitoring of vehicle movements, bin status, and depot operations, providing municipal administrators with actionable insights and control over field activities. By integrating traffic simulation, the Vehicle Routing Problem (VRP), and an interactive visualization layer, the proposed system presents a scalable, modular solution tailored for the evolving waste management needs of Indian metropolitan regions.

II. SYSTEM ARCHITECTURE

The system architecture follows a layered and modular design that supports scalability, real-time responsiveness, and ease of maintenance. It is structured around three primary components: the user-facing frontend, the computational backend, and a set of integrated third-party services. Together, these components work in unison to dynamically optimize waste collection routes and provide municipal authorities with full visibility and control over ongoing operations. The architecture is designed to facilitate seamless data flow, low-latency interactions, and adaptability to real-world urban conditions. A high-level view of the system's architecture is provided in *Figure 1*, which illustrates the key modules and their interconnections.

A. Frontend: User Dashboard

At the core of the user interface is a real-time dashboard tailored for waste management staff and municipal administrators. This dashboard functions as the central hub for visualization, data interaction, and operational control. It is designed to be intuitive yet powerful, offering a comprehensive overview of the current status of waste collection activities throughout the city. The dashboard plays a critical role in both planning and real-time monitoring, allowing users to interact with system outputs, make manual adjustments if necessary, and gain insights into overall operational efficiency.A key feature of the dashboard is its input panel, where users are required to provide essential configuration data before route optimization begins. These inputs include the number of garbage trucks available for deployment, the capacity constraints of each truck, the current or predicted fill levels of dustbins, and specific fuel consumption rates per kilometre for each vehicle. Users may also specify service window preferences if there are designated collection times for particular zones. These inputs are vital for personalizing the optimization strategy and ensuring that the generated routes are aligned with practical limitations and sustainability goals.

Once the inputs are configured, the system generates optimized routes that are immediately displayed on an interactive map embedded within the dashboard. This map, powered by the Mapbox API, provides a geographic representation of the entire operational landscape. It shows current truck locations, bin statuses (e.g., full, partially full, or empty), and highlights real-time traffic congestion using color-coded overlays. The map updates dynamically as trucks move along their routes, offering operators a live, spatial perspective of the system in action and enabling them to intervene when necessary—such as rerouting a vehicle due to unexpected bin overflow or road blockage.Complementing the map is a statistical dashboard that presents key performance indicators (KPIs) in real time. This panel displays data such as total distance travelled, estimated fuel consumption, number of bins serviced, average response time, and cost per route. These metrics are continuously updated and offer both tactical insights for short-term improvements and strategic analytics for long-term planning. Overall, the dashboard transforms complex operational data into actionable intelligence, empowering decision-makers to manage urban waste collection with precision and efficiency.

B. Backend: Flask Framework and Optimization Engine

The backend of the system is implemented using the Flask web framework, a lightweight yet powerful Python-based environment ideal for building API-driven applications. This backend is responsible for managing all computational logic, processing user inputs, executing optimization algorithms, and facilitating communication between the frontend interface and the underlying data infrastructure. It serves as the brain of the entire architecture, orchestrating each module's function to ensure a smooth and intelligent routing process.One of the foundational components of the backend is the Capacitated Vehicle Routing Problem (CVRP) solver. This algorithm is designed to compute optimal routes for multiple vehicles that must service a set of locations, each with specific demand levels, without exceeding the capacity of any vehicle. The CVRP solver takes into account various constraints, such as bin fill levels, truck capacities, service times, and distance thresholds. Based on this information, it generates a set of efficient routes that minimize travel distance while maximizing resource utilization and collection coverage. The algorithm is flexible and can be configured to accommodate multiple depots or specialized collection rules in future extensions of the system.

In addition to traditional optimization techniques, the backend integrates a reinforcement learning (RL) model that introduces an element of adaptability and intelligence into route planning. Trained on synthetic and historical data, this model learns patterns in waste generation, traffic flow, and route efficiency over time. It continuously updates its policy based on real-time data, enabling the system to predict which bins are most likely to reach capacity soon and prioritize those in the routing plan. By combining the strengths of deterministic optimization (CVRP) and adaptive learning (RL), the backend achieves a balance between robustness and responsiveness, ensuring that routing decisions evolve alongside changing urban dynamics.

C. External Services and Real-Time Integration

To generate routing solutions that are not only mathematically optimal but also practically viable, the system relies on several third-party APIs that provide real-time contextual data. Chief among these is the Mapbox API, which plays a critical role in enriching route planning with real-world geographic and traffic information. This API provides up-to-date data on traffic congestion, road types, one-way restrictions, and estimated travel durations. This data is crucial for generating realistic travel plans and for dynamically rerouting vehicles in response to live urban events such as traffic jams, road closures, or public events.

Once initial routes are computed using CVRP and possibly refined using the RL agent, the system leverages real-time inputs to validate or adjust these routes. Using data from Mapbox and internal route intelligence, the backend continuously evaluates current conditions to determine if rerouting is necessary. If so, it triggers an update to the route assignments and instantly pushes the new instructions to the frontend dashboard.

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This rerouting mechanism ensures operational resilience and responsiveness, reducing the likelihood of missed collections or delays.Moreover, the system supports the generation of multiple route options based on constraints such as minimum fuel usage, shortest time, or least number of bins skipped. These alternatives are evaluated and presented visually to the user, allowing administrators to select the plan that best aligns with current priorities. This dynamic routing capability ensures optimal resource distribution across multiple service zones, contributing to more sustainable and cost-effective waste management strategies.

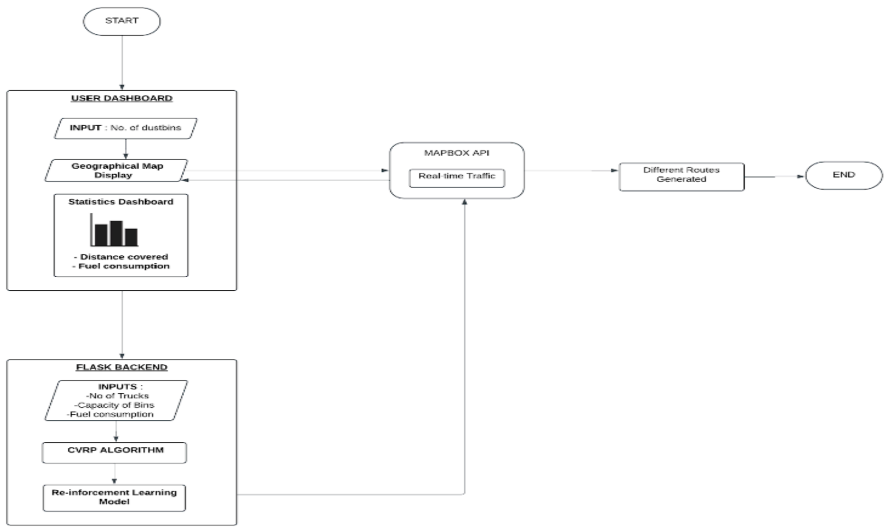

Fig. 1 System architecture of the dynamic route optimization platform

III. METHODOLOGY

The development of the dynamic waste collection system follows a structured and iterative methodology encompassing four key phases: data preparation, route optimization, traffic simulation, and visualization. This framework integrates multiple technologies and tools to enable efficient, scalable, and adaptive route planning tailored to real-time urban constraints. Each component plays a critical role in ensuring the operational effectiveness of the system across varying urban conditions. A high-level overview of the outputs, including visual interfaces and route simulations, is presented in *Figure 2* and *Figure 3*, which depict the interactive dashboard and map-based routing interface, respectively. The subsections below elaborate on each methodological phase and their respective implementations.

A. Data Simulation and Preparation

To replicate real-world operational conditions and support the testing of route optimization algorithms, a comprehensive synthetic dataset was created. This dataset represents a realistic urban setting with multiple waste collection points, each modelled to include relevant parameters affecting route planning. The synthetic data was designed to simulate bin-level waste generation behaviours observed in densely populated city zones.

Each bin entry in the dataset includes geographic coordinates (latitude and longitude), a unique bin identifier, current simulated waste levels (volume-based), the timestamp of the last collection, and a bin priority tag to reflect collection urgency. These attributes enable the system to differentiate between regular pickups and high-priority collections, such as in public spaces or commercial areas. In addition to bin-level data, the system incorporates configuration details for vehicle depots and dump yards. Depots are used as the starting and ending points for collection vehicles, while dump yards serve as unloading sites, each with defined capacity limits and associated time penalties for unloading cycles. This configuration helps simulate realistic operational workflows, including the need for intermediate dumping during extended routes.

B. Route Optimization Using VRP

At the core of the system lies a robust routing logic based on the classical Vehicle Routing Problem (VRP), adapted to support dynamic inputs. The VRP was formulated as a combinatorial optimization problem with the objective of minimizing total route distance and fuel consumption, while ensuring that operational constraints are strictly respected.

The optimization model accounts for several constraints including vehicle capacity limits, individual bin service times, maximum route durations, and road network distance metrics. The solver was designed to handle dynamic updates, allowing it to respond to real-time events such as changes in bin fill status, traffic variations, and vehicle availability. For example, if a bin reaches an overflow threshold or a vehicle reports full capacity mid-route, the system recomputes route allocations to accommodate the updated state. This ensures that the routing strategy remains effective and responsive throughout the collection cycle. The output of this phase is a set of optimized and feasible vehicle routes, ready to be simulated and visualized on the city map, as seen in *Figure 2.*

C. Traffic Simulation Using SUMO

To validate the practicality of the optimized routes in real-world traffic conditions, the system integrates the Simulation of Urban Mobility (SUMO) platform. SUMO allows for the high-fidelity modelling of traffic flow and road network dynamics, making it ideal for simulating municipal fleet operations. The road network used in the simulation was derived from real-world OpenStreetMap (OSM) data of Bangalore. This data was converted into a SUMO-compatible format using the net convert tool and included detailed attributes such as intersections, traffic signals, road types, and directional constraints.

Garbage collection vehicles were modelled as SUMO vehicles with parameters such as acceleration, speed, and vehicle length tailored to match real-world truck characteristics. The optimized routes generated by the VRP solver were fed into SUMO using the TraCI API, enabling real-time interaction between the routing engine and the simulator. Through this integration, the system could simulate truck movements, observe congestion behaviour, and identify route bottlenecks. Performance metrics such as total travel time, distance covered, and estimated fuel consumption were collected during the simulation. These metrics offered valuable insights into route efficiency under various traffic scenarios, particularly during peak congestion hours. The simulations also highlighted operational delays caused by traffic signals and intersection density, allowing the optimization engine to refine routes accordingly. A visual example of these simulations with mapped routes and active vehicle paths is provided in *Figure 2*.

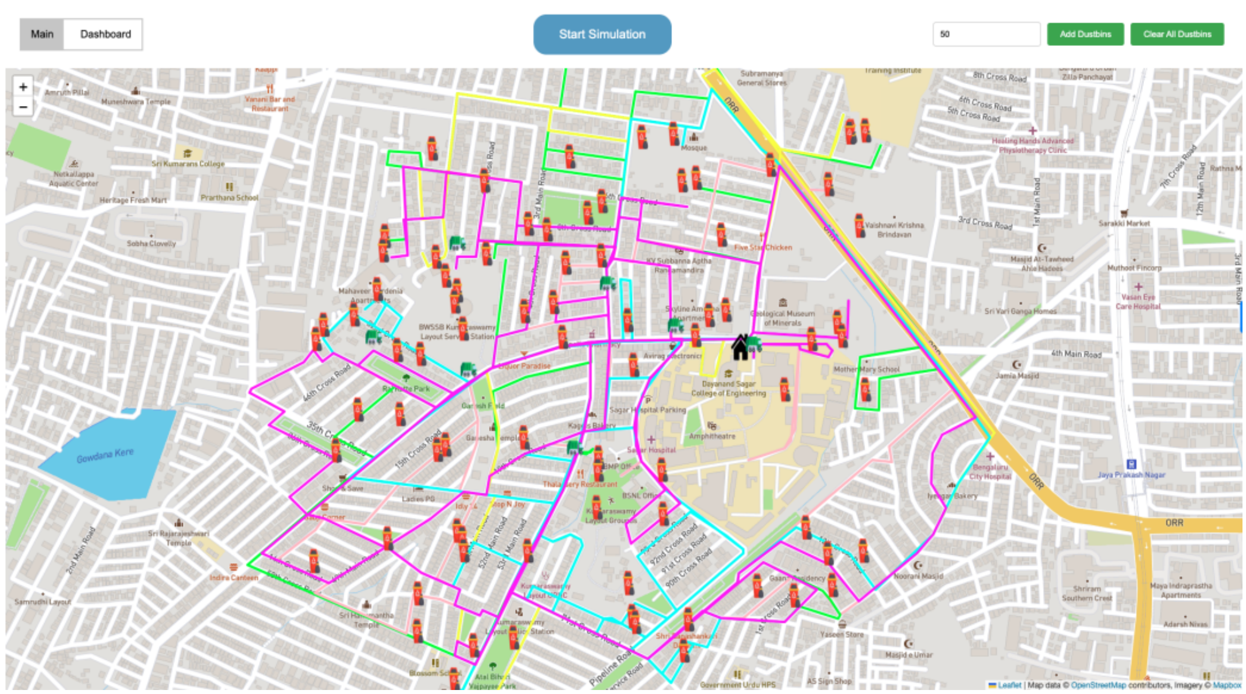

Fig. 2. Visualization of dynamic waste collection routes generated by the optimization engine

D. Dashboard and Visualization Layer

The final phase of the methodology focuses on real-time visualization and user interaction. A web-based dashboard was developed to assist municipal administrators in monitoring and managing the waste collection process. The dashboard serves as the primary interface through which users interact with the system's outputs, offering an intuitive and interactive environment for decision-making. A snapshot of this dashboard, showing active vehicles, bin statuses, and route overlays, is presented in *Figure 3.*

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The dashboard includes a live map that tracks garbage truck locations in real-time, displaying each truck's route, current position, and service progress. Bins are visually represented with color-coded markers indicating their status—such as collected, pending collection, or overflowing. Users can interact with these markers to retrieve metadata, such as bin ID, last serviced time, and priority level. Additionally, the dashboard supports dynamic route generation and rerouting capabilities. If traffic or bin conditions change mid-operation, the system pushes updated routes to the dashboard, allowing users to approve and deploy them seamlessly.

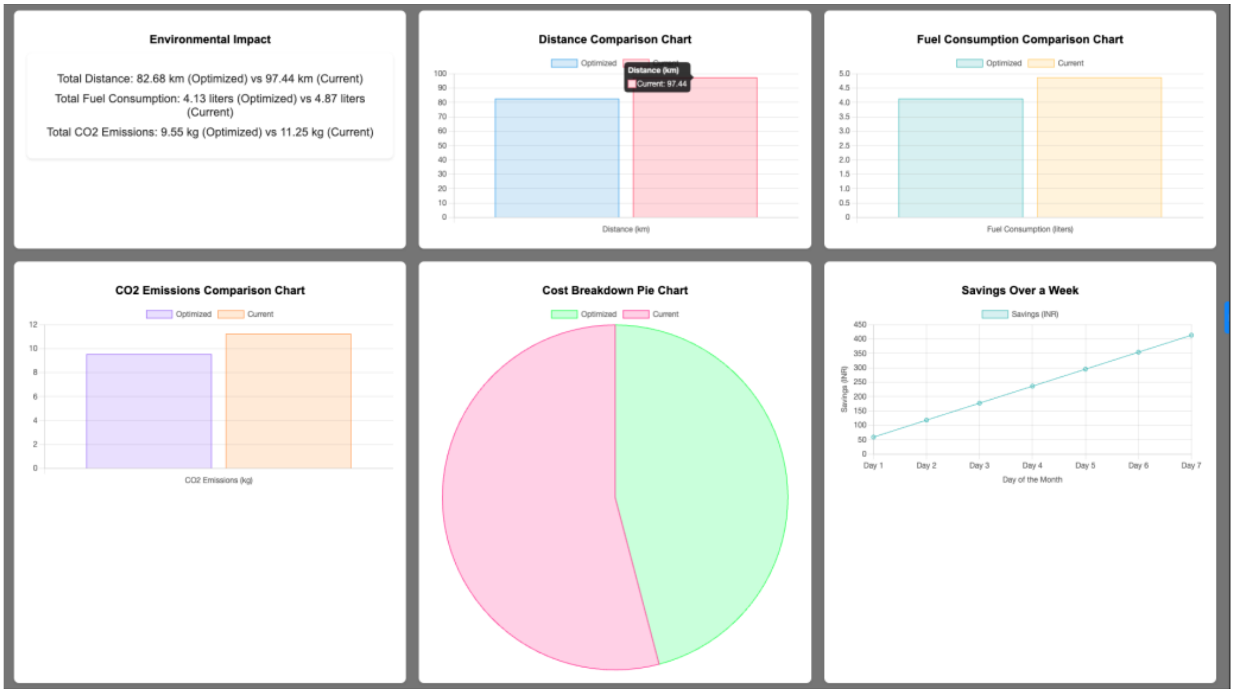

Fig 3. The real-time dashboard interface for municipal operators

To support operational analysis, the dashboard also generates daily reports summarizing performance indicators like total distance travelled, fuel consumption, average collection time, and number of bins serviced. These reports assist in evaluating the system's effectiveness over time and inform future policy or resource allocation decisions. Overall, the dashboard bridges the gap between backend computations and field-level operations, turning data into actionable intelligence for smart urban waste management.

IV. RESULTS AND DISCUSSION

The proposed dynamic routing system was evaluated extensively using a synthetically generated dataset and tested within the SUMO (Simulation of Urban Mobility) simulation environment. The evaluation focused on key performance indicators such as fuel efficiency, collection time, route adaptability, and user experience via the dashboard interface. The goal was to benchmark the performance of the dynamic routing model against conventional static route planning methodologies typically used in urban waste management systems.The results demonstrated a notable improvement in overall operational efficiency. Specifically, fuel consumption was reduced by approximately 17% compared to static routing systems. This improvement can be attributed to several factors: the elimination of redundant paths, shorter and more optimized travel routes, and effective bin prioritization based on urgency and location. These changes resulted in more compact route paths and fewer unnecessary detours, directly translating to cost savings and reduced environmental impact in terms of lower carbon emissions.

In terms of time efficiency, the dynamic routing system reduced the average waste collection time by nearly 22%. The system achieved this by prioritizing high-fill bins and dynamically adjusting the route based on real-time traffic data. Congested routes were proactively avoided using live data from the Mapbox API, ensuring that waste collection vehicles spent less time in traffic and more time servicing areas that needed immediate attention. This led to quicker turnarounds per collection cycle and allowed the same fleet to cover more ground within a given time window.Another key observation was the reduction in idle stops and non-essential bin visits. Traditional systems often send vehicles to bins regardless of their status, resulting in inefficiencies. The proposed system, on the other hand, used bin fill levels as a decision factor, thereby avoiding unnecessary stops.

This not only optimized fuel usage and time but also decreased wear and tear on vehicles, contributing to lower maintenance costs and extended fleet longevity.

In conclusion, the results validate the effectiveness of the proposed system in real-world urban settings. The integration of optimization algorithms, real-time data, and traffic-aware simulations enabled a significant leap in efficiency over traditional methods. By reducing fuel usage, travel time, and operational strain while improving service coverage and response time, the system offers a compelling case for adoption in smart city waste management initiatives.

V. CONCLUSION

This paper presents a comprehensive and dynamic waste collection routing system, combining real-time optimization algorithms, traffic simulation via SUMO, and an interactive monitoring dashboard. The integration of these components offers an intelligent, responsive solution to the challenges faced by static routing mechanisms in growing metropolitan environments.The system has demonstrated clear improvements in fuel efficiency, time management, and operational transparency, paving the way for smarter and greener waste management infrastructures. Additionally, the modular architecture ensures adaptability to different city layouts and administrative requirements.

Future enhancements planned for the system include:

1) IoT Integration: Direct incorporation of real-time sensor data from smart garbage bins to further improve accuracy and response time.
2) Scalability Testing: Expanding the implementation to larger datasets and multiple urban centres to test generalizability and robustness.
3) Sustainability Analytics: Integration of vehicle-specific emissions tracking and carbon footprint analysis to evaluate environmental impact.
4) Mobile App for Drivers: To facilitate seamless communication and route updates, especially in areas with fluctuating network availability.

Through continuous improvements and smart city integration, this system aspires to become a cornerstone solution in the modernization of urban public services.

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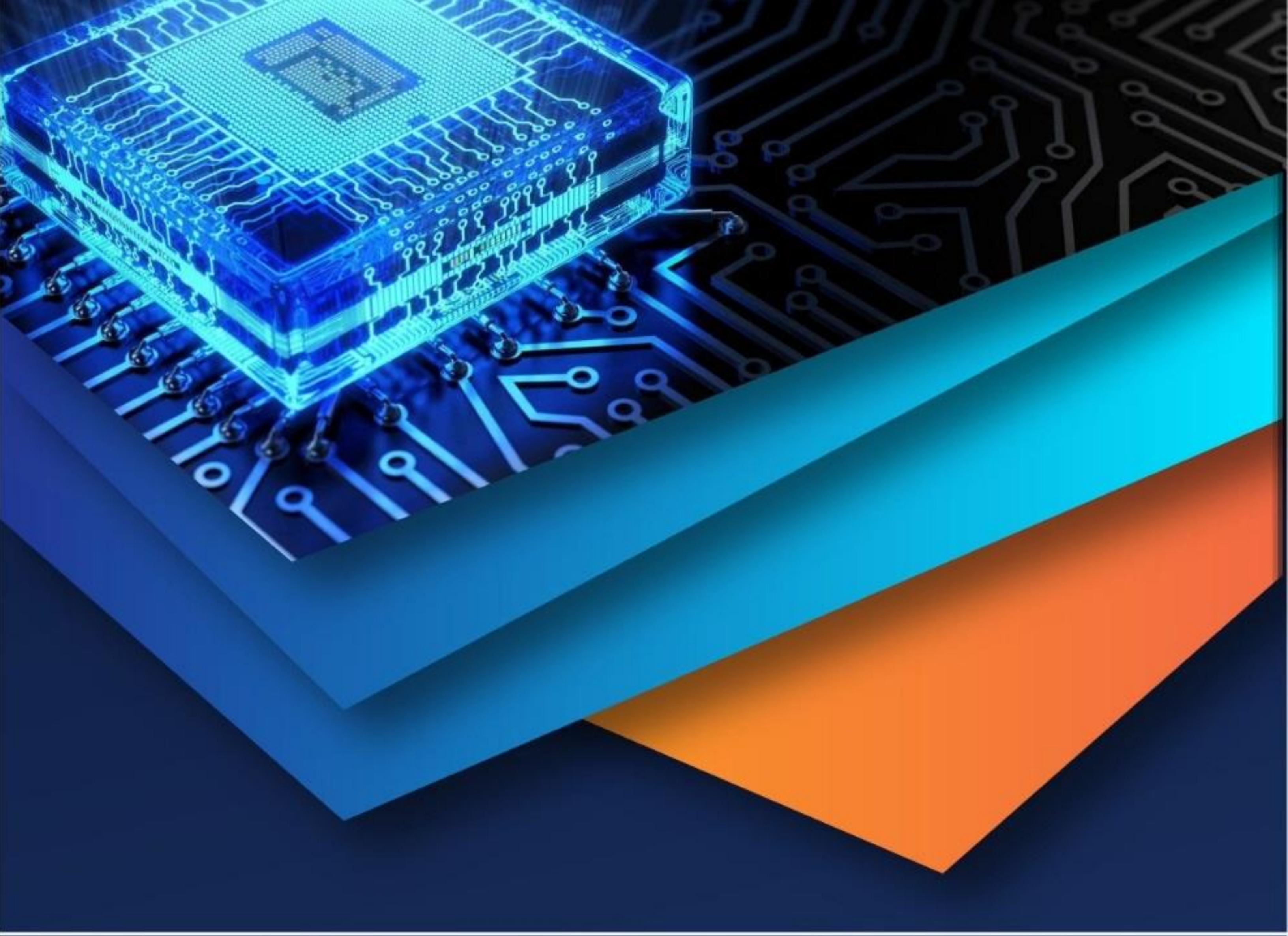

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