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SmartPack: AI-Powered Box Size Packaging Optimization Platform for SMEs and MSMEs

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Abstract: Packaging inefficiency is a common challenge for Small and Medium Enterprises (SMEs) and Micro, Small, and Medium Enterprises (MSMEs), where box sizes are often selected through manual estimation, leading to poor space utilization, higher transportation costs, and increased material waste. This paper presents SmartPack, a cloud-based packaging optimization platform designed to improve box size selection and packaging efficiency through structured computational analysis. The system analyzes product dimensions such as length, width, height, and weight, and compares them with predefined box configurations to recommend the most suitable packaging option. In addition, the platform incorporates digital twin–based three-dimensional visualization to simulate product placement within the recommended box before actual packaging. The system also evaluates packaging cost and space utilization to support data-driven decision making. Experimental results indicate significant improvements in packaging performance, with space utilization increasing from approximately 65% to nearly 85–90% and packaging costs reduced by around 15–25%. These findings demonstrate that SmartPack provides an efficient and scalable solution for intelligent packaging optimization, helping SMEs and MSMEs reduce operational costs, improve logistics efficiency, and promote sustainable packaging practices.
Keywords: Packaging optimization, box size prediction, small and medium enterprises (SMEs), logistics efficiency, sustainable packaging, digital twin simulation.

I. INTRODUCTION

Packaging plays a central role in supply chain management, affecting product protection, transportation efficiency, and overall business costs. For Small and Medium Enterprises (SMEs) and Micro, Small, and Medium Enterprises (MSMEs), packaging decisions directly influence profitability and customer satisfaction. However, many small-scale businesses continue to rely on manual estimation when selecting box sizes and packaging materials. Without systematic evaluation, products are often packed in cartons that are larger than necessary, leading to poor space utilization, higher shipping charges due to increased volumetric weight, and excessive use of packaging materials. Over time, these inefficiencies reduce operational efficiency and contribute to avoidable environmental waste.

A major challenge faced by SMEs and MSMEs is the lack of accessible digital tools that support data-driven packaging decisions. While large enterprises may implement advanced logistics optimization systems, small businesses often operate without structured decision-support mechanisms for packaging analysis and cost evaluation. This gap creates a need for an affordable, scalable, and user-friendly digital solution specifically designed for resource-constrained enterprises.

To address this need, this paper introduces SmartPack, a web-based packaging optimization platform developed to improve box size selection and material utilization through structured data analysis. The system enables users to enter product details such as dimensions and weight, which are analyzed using volume-based evaluation techniques to recommend suitable packaging configurations. In addition, a digital twin-based three-dimensional simulation module allows users to visualize product placement within the recommended box before actual packaging is performed. This feature helps reduce trial-and-error processes and improves decision accuracy.

The platform is designed using a modular architecture that includes user interaction, secure authentication, optimization processing, and data management components. Through an interactive dashboard, SMEs can monitor packaging cost, space utilization, and material efficiency. By combining modern web technologies with scalable backend services and structured optimization logic, SmartPack aims to enhance packaging efficiency, reduce operational costs, and support sustainable packaging practices. The proposed system establishes a practical framework for intelligent packaging optimization tailored to small and medium-scale enterprises.

II. LITERATURE REVIEW

Packaging optimization and intelligent packaging systems have gained significant attention due to the increasing demand for efficient logistics and sustainable packaging solutions. Researchers have explored various techniques including machine learning, artificial intelligence, and optimization algorithms to improve packaging efficiency and reduce material waste.

Gurumoorthy and Hinge proposed a decision-tree-based framework to determine optimal box dimensions for product shipments. Their approach clusters products based on dimensional characteristics and recommends appropriate box sizes that minimize unused space and shipping costs. The results demonstrate that optimized box configurations can significantly reduce packaging volume and transportation expenses [1].

Recent advancements in intelligent packaging technologies have also incorporated artificial intelligence to improve product monitoring and packaging efficiency. Li et al. reviewed the application of AI-based intelligent packaging systems for monitoring food freshness and ensuring product quality. Their study highlighted the role of artificial intelligence, sensors, and data analysis in enhancing packaging safety and efficiency across supply chains [2].

Artificial intelligence adoption in small and medium enterprises (SMEs) has also been widely studied. Peretz-Andersson et al. investigated how manufacturing SMEs implement artificial intelligence technologies to improve operational efficiency and digital transformation. Their study emphasizes the importance of resource orchestration and technological capability in successfully integrating AI into business processes [3].

Sustainable packaging has become an important research area due to environmental concerns and increasing packaging waste. Verma et al. presented a review of AI-driven sustainable packaging solutions that focus on optimizing material selection, packaging design, and environmental impact. The study demonstrates how artificial intelligence can assist companies in developing environmentally responsible packaging systems [4].

Several studies have also explored the role of artificial intelligence in optimizing packaging design and logistics efficiency. Zghair and Konathala developed an AI-based framework to optimize packaging design in e-commerce systems. Their approach utilizes machine learning algorithms to analyze product characteristics and recommend efficient packaging configurations that reduce material usage and operational costs [5].

Similarly, Kumar et al. discussed the concept of Packaging 4.0, which integrates artificial intelligence, machine learning, and digital technologies into packaging operations. Their research highlights how AI-driven systems can improve packaging design, quality inspection, supply chain management, and production efficiency [6].

The impact of artificial intelligence and machine learning in large-scale e-commerce packaging systems has also been investigated. Dandge analyzed the application of AI algorithms in optimizing packaging decisions within Amazon’s logistics network. The study shows that AI technologies significantly reduce packaging material consumption and improve shipment efficiency through data-driven packaging strategies [7].

A broader review of machine learning applications in packaging optimization was conducted by Alper et al., who analyzed research trends related to packaging design, quality control, predictive maintenance, and supply chain optimization. Their systematic review emphasizes the growing importance of machine learning techniques in improving packaging processes and operational efficiency [8].

Logistics packing optimization has also been addressed through advanced algorithms. Ma et al. proposed a three-dimensional container loading algorithm that integrates heuristic methods and genetic algorithms to maximize container space utilization while satisfying practical constraints. Their work demonstrates the effectiveness of algorithm-based packing methods for logistics applications [9].

In addition, predictive technologies have been applied to improve operational efficiency in SMEs. Yel et al. studied the application of AI-based predictive models in inventory optimization for SMEs. Their research shows that predictive analytics can improve resource management and operational decision-making, helping SMEs enhance their competitiveness in dynamic market environments [10].

Although previous studies have explored packaging optimization, AI-driven packaging design, and logistics algorithms, most existing solutions focus on large-scale industrial systems or specialized applications. Limited research has focused on developing integrated and accessible packaging optimization platforms specifically designed for SMEs and MSMEs. Therefore, there is a need for a scalable and user-friendly system that combines packaging optimization, cost evaluation, and visualization capabilities.

To address this research gap, the proposed SmartPack platform integrates box size optimization, digital twin simulation, packaging cost evaluation, and sustainability-based packaging strategies within a unified architecture. This system aims to provide SMEs with an efficient and practical solution for intelligent packaging optimization.

III. PROPOSED SYSTEM

The SmartPack system is developed as a cloud-based packaging optimization platform specifically designed for Small and Medium Enterprises (SMEs) and Micro, Small and Medium Enterprises (MSMEs). The system follows a structured multi-stage workflow that includes secure authentication, product data acquisition, sustainability configuration, computational optimization, digital twin visualization, and performance evaluation. The modular design improves scalability, maintainability, and efficient coordination between functional components.

A. Sustainability and Material Selection Module

This module allows users to choose packaging strategies aligned with cost efficiency and environmental considerations. Users can select sustainability-oriented, balanced, or cost-driven configurations. Material options, including single-wall, double-wall, and triple-wall corrugated boards, are evaluated based on strength, load-bearing capacity, and economic feasibility. This integrated approach connects environmental responsibility with practical cost analysis.

B. Box Size Optimization Module

The box size optimization engine is the main part of the SmartPack system. It checks the dimensions of the product and compares them with the available box sizes stored in the system database. The main goal is to choose a box that reduces unused space while still meeting safety and size requirements.

The system looks at the product’s length, width, and height and compares these measurements with the available box sizes. Based on this comparison, the system analyzes how efficiently the product can fit inside the box.

Finally, the system selects the box that provides the best space usage while keeping enough protective space around the product. This helps reduce empty space inside the box and decreases unnecessary packaging material.

C. Digital Twin Simulation Module

Following optimization, the system generates a three-dimensional digital twin model illustrating product placement within the recommended box. The visualization displays labeled dimensions and spatial alignment to verify fitting precision. This simulation allows users to confirm packaging feasibility before physical implementation, significantly reducing manual adjustments and trial-and-error processes.

D. Cost Evaluation Module

The cost evaluation component estimates packaging expenditure based on selected box dimensions and material specifications. It compares baseline manual packaging cost with optimized system-generated cost to identify potential savings. This comparative financial insight highlights the economic benefits of structured packaging optimization.

E. Integration Module

SmartPack supports integration with Enterprise Resource Planning (ERP) and warehouse management systems through API-based communication. The layered architecture enables seamless data exchange and workflow compatibility, ensuring scalability and adaptability for future enhancements.

F. User-Friendly Interface

The SmartPack application is designed with a simple, intuitive, and user-friendly interface that allows users to interact with the system easily. The platform is developed to ensure that even users with limited technical knowledge can navigate the system without difficulty.

The interface enables users to enter product details, view optimization results, and access packaging recommendations in a clear and organized manner. This design improves usability and ensures that small and medium enterprises can efficiently utilize the platform for packaging optimization.

IV. PROPOSED ARCHITECTURE

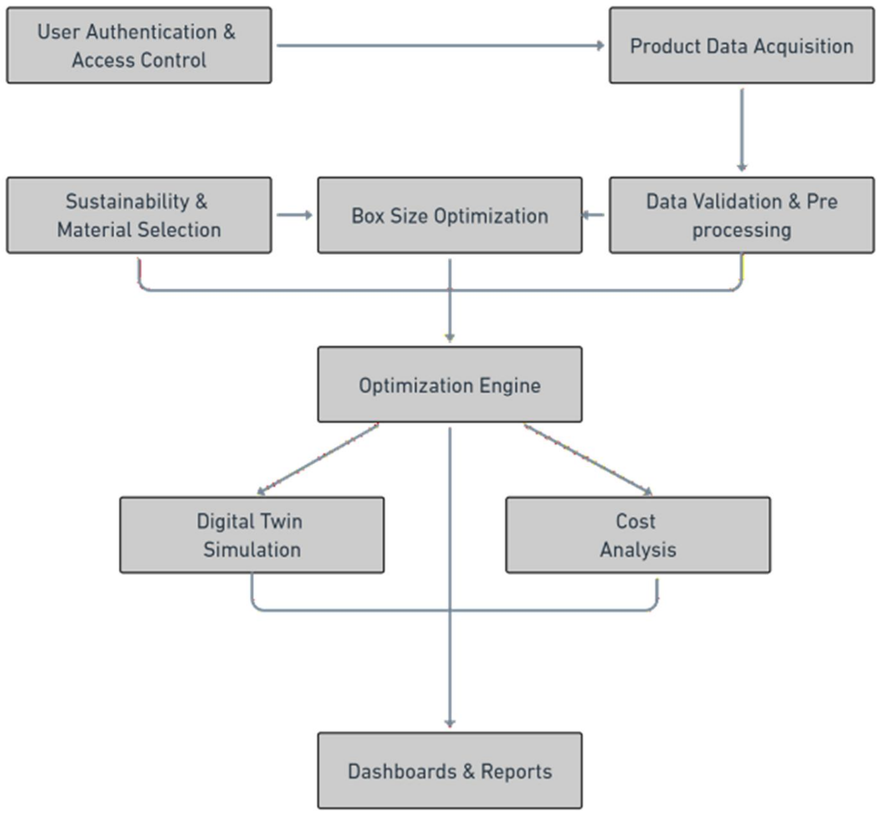

Fig1-Architecture of SmartPack Platform

Figure 1 presents the abstract architecture of the SmartPack Packaging Optimization Platform, designed to support Small and Medium Enterprises (SMEs) and Micro, Small, and Medium Enterprises (MSMEs) through a secure and layered system. All users interact with the platform through a web-based interface supported by an authentication and access control mechanism that ensures secure login, session management, and role-based authorization. This mechanism ensures that only authorized users can access packaging optimization services, view system outputs, and generate reports. The architecture emphasizes controlled system access, ensuring that users interact only with the functionalities necessary for packaging configuration, analysis, and reporting.

The core functionality of the platform is handled within the application service layer, which manages communication between user interfaces and backend processing modules. This layer integrates multiple services including product data processing, sustainability and material selection, box size optimization, digital twin simulation, and packaging cost evaluation. The optimization module evaluates product dimensions and compares them with predefined box configurations to determine the most efficient packaging option. The digital twin simulation module provides a three-dimensional visualization of product placement within the selected box, allowing users to verify packaging feasibility before implementation.

All system data, including product inputs, box dimension libraries, packaging material specifications, optimization outputs, and historical records, are maintained within a centralized database layer that ensures reliable data storage and retrieval. In addition, the platform supports integration with external enterprise systems such as Enterprise Resource Planning (ERP) and warehouse management systems through an integration layer that enables secure API-based communication. This layered architectural design, as illustrated in Figure 1, ensures scalability, modularity, and efficient interaction between users, application services, optimization modules, external systems, and data storage components, making the SmartPack platform suitable for practical deployment in SMEs and MSMEs.

V. METHODOLOGY

The SmartPack system adopts a structured and sequential methodology to achieve accurate box size prediction, improved material utilization, and cost-efficient packaging decisions for SMEs and MSMEs. The methodology is designed to ensure secure system interaction, reliable computational analysis, and measurable performance evaluation. Each stage of the workflow contributes to systematic packaging optimization while maintaining scalability and operational efficiency.

A. User Authentication and Access Control

The process begins with a secure authentication mechanism that verifies user credentials before granting access to system services. Role-based access control ensures that only authorized users can interact with optimization and reporting modules. Session management techniques maintain data confidentiality and prevent unauthorized operations. This controlled access structure strengthens system reliability and safeguards enterprise data.

B. Product Data Acquisition

Once authenticated, users provide structured product inputs including length, width, height, weight, and fragility level. These parameters represent the core variables required for packaging evaluation. Accurate data acquisition is essential because dimensional precision directly influences volume computation and box selection accuracy.

C. Data Validation and Preprocessing

The system performs logical validation to confirm that all input values are positive, realistic, and within permissible operational ranges. Inconsistent or incomplete entries are flagged to avoid computational inaccuracies. Preprocessing ensures standardized dimensional representation prior to optimization analysis.

D. Sustainability and Material Selection

Users can select packaging strategies based on business priorities such as cost minimization, balanced optimization, or sustainability-focused packaging. The system evaluates available material options according to strength, load capacity, and environmental considerations. This module integrates financial and sustainability perspectives into packaging decision-making.

E. Volume and Space Utilization Analysis

Product volume is calculated using:

$$\text{Vproduct} = L \times W \times H$$

where L, W, and H represent product length, width, and height.
Space utilization is then determined as:

$$\text{Utilization (\%)} = \text{Vproduct} / \text{Vbox} \times 100$$

These calculations quantify packing efficiency and identify void space within candidate box configurations.
Additionally, the void space inside the box is estimated as:

$$\text{Void Space} = V_{box} - V_{product}$$

where V_{box} represents the volume of the selected box and $V_{product}$ represents the volume of the product. This value indicates the unused space remaining inside the packaging container.

F. Optimization Logic Execution

The optimization engine compares computed utilization metrics across available box dimensions and selects the configuration that maximizes utilization while maintaining structural safety margins.

G. Digital Twin Simulation

A three-dimensional digital twin model visualizes product placement inside the selected box. This simulation verifies spatial alignment and reduces dependency on manual estimation.

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H. Packaging Cost Evaluation

The system estimates material cost and compares manual and optimized packaging configurations to quantify potential savings.

I. Dashboard and Reporting

Final optimization results, including box dimensions, utilization ratio, void percentage, and cost savings, are displayed through an interactive dashboard. Historical data storage supports performance monitoring and business documentation.

VI. RESULTS

The SmartPack system was evaluated through controlled functional testing using representative product dimensions and packaging scenarios. The objective of evaluation was to analyze optimization accuracy, space utilization efficiency, computational response time, and clarity of result visualization. The results confirm that the proposed platform effectively improves packaging efficiency while maintaining real-time system performance.

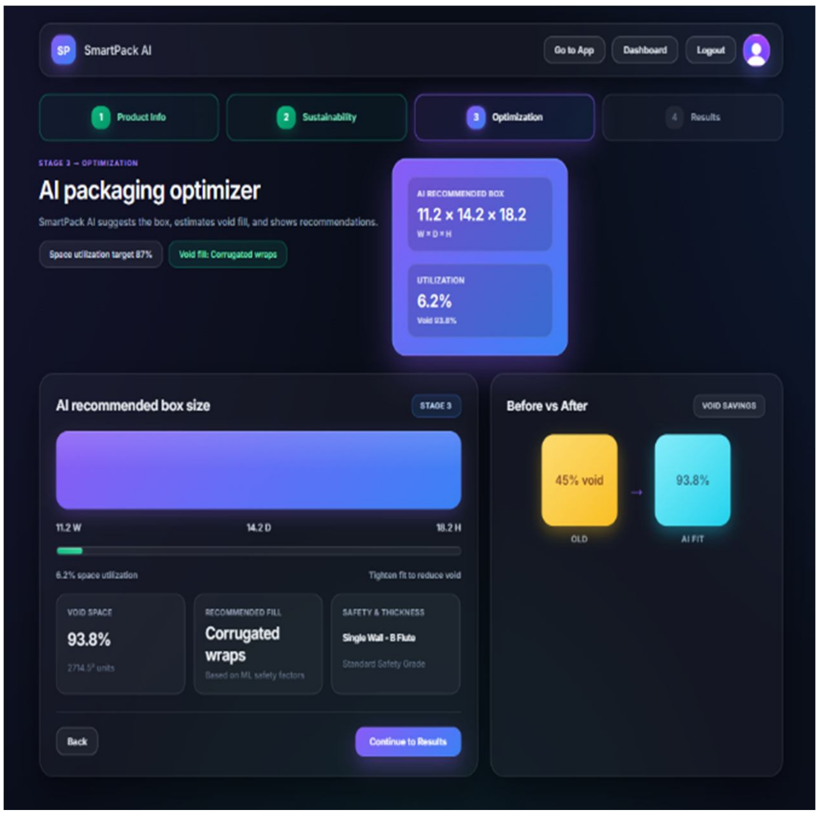

Fig2-Box Size Optimization

Figure 2 illustrates the optimization output generated by the SmartPack engine. Based on the provided product parameters, the system recommended a box size. The optimization module computed volumetric parameters and selected the most appropriate configuration from predefined box datasets using deterministic comparison logic.

The dashboard displayed key spatial metrics, including space utilization percentage and void analysis. Comparative visualization (“Before vs. After”) indicated a significant reduction in unused space when compared to conventional manual estimation. While baseline packaging scenarios typically showed approximately 45% void space, the optimized configuration demonstrated improved spatial alignment and compact product placement. This confirms that structured dimensional matching enhances carton compactness and reduces unnecessary filler usage.

System response time remained within 1–2 seconds, demonstrating efficient computational execution and stable backend processing. Since the system operates using rule-based volume evaluation rather than machine learning inference, performance measurement was conducted using API latency monitoring and request–response validation logs.

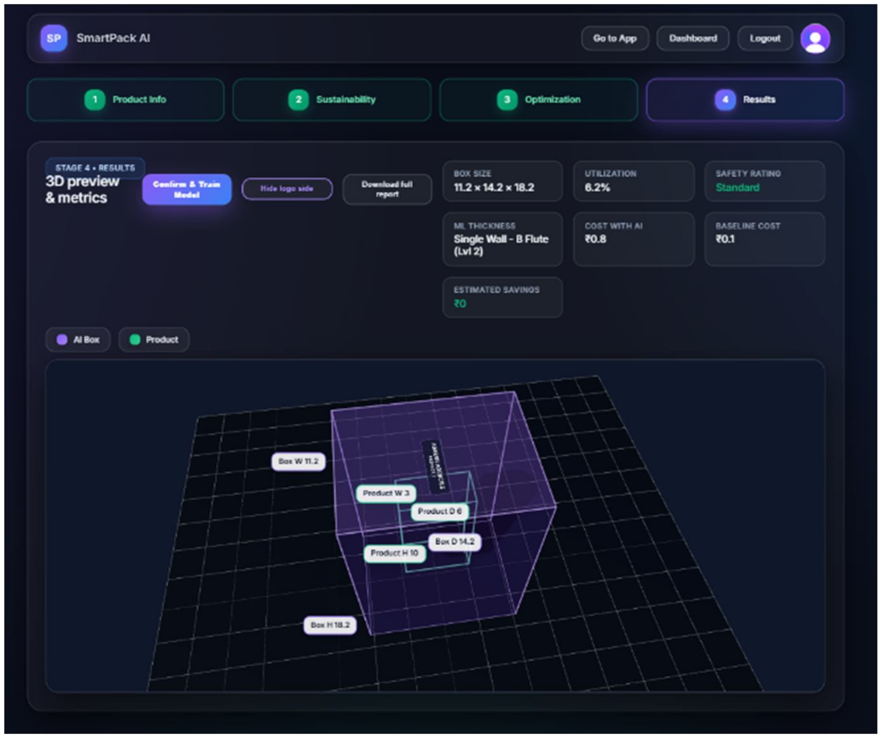

Fig3-Digital Twin Validation

Figure 3 illustrates the three-dimensional digital twin visualization produced after the optimization process. The simulation displays the recommended box dimensions along with the internal positioning of the product, including clearly labeled width, depth, and height measurements. This visual representation allows users to verify whether the product fits correctly within the selected packaging configuration before actual packaging takes place.

The digital twin feature reduces reliance on manual estimation and helps eliminate repetitive trial-and-error adjustments during packaging. By providing an interactive 3D preview, the system improves user understanding and supports more accurate and data-driven packaging decisions.

The optimization dashboard also presents important information such as material specifications, safety indicators, and cost comparison details. Experimental testing showed that the optimized packaging approach reduced overall packaging costs by approximately 15–25% compared to traditional manual methods. Additionally, space utilization improved from nearly 65% to around 85–90%, which contributes to lower material usage and more efficient transportation.

The reporting component of the system successfully produced downloadable summaries and maintained historical optimization records without affecting system stability. These results demonstrate that SmartPack delivers consistent optimization performance, measurable cost savings, and improved packaging efficiency, making it a practical solution for SMEs and MSMEs.

VII. CONCLUSIONS

This study introduced SmartPack, a packaging optimization platform developed to enhance box size selection, improve space utilization, and reduce packaging costs for SMEs and MSMEs. The proposed system combines volume-based evaluation techniques, packaging cost analysis, and digital twin visualization to support structured and data-driven packaging decisions.

The evaluation results demonstrate notable improvements in packaging efficiency. Space utilization increased from approximately 65% under conventional packaging practices to nearly 85–90% using the optimized approach. Additionally, packaging expenses were reduced by about 15–25%, indicating clear economic benefits. The system also delivers recommendations in real time while maintaining low computational complexity.

Overall, the SmartPack platform provides a practical and scalable solution for intelligent packaging optimization. By improving packaging efficiency and reducing material waste, the system supports more cost-effective and sustainable logistics operations for SMEs and MSMEs.

VIII. FUTURE SCOPE

Future enhancements of the SmartPack platform can focus on expanding its functionality and system integration capabilities. One potential improvement is the integration of real-time shipping and logistics APIs to estimate transportation costs based on package dimensions, weight, and delivery location.

In addition, developing a mobile-based interface would allow users to access the platform directly in warehouse or production environments, enabling faster packaging decisions. Incorporating predictive analytics techniques could further improve box size recommendations by analyzing historical packaging data. Furthermore, the inclusion of sustainability indicators, such as environmental impact and carbon footprint analysis, would strengthen the platform's role in supporting environmentally responsible packaging practices for SMEs and MSMEs.

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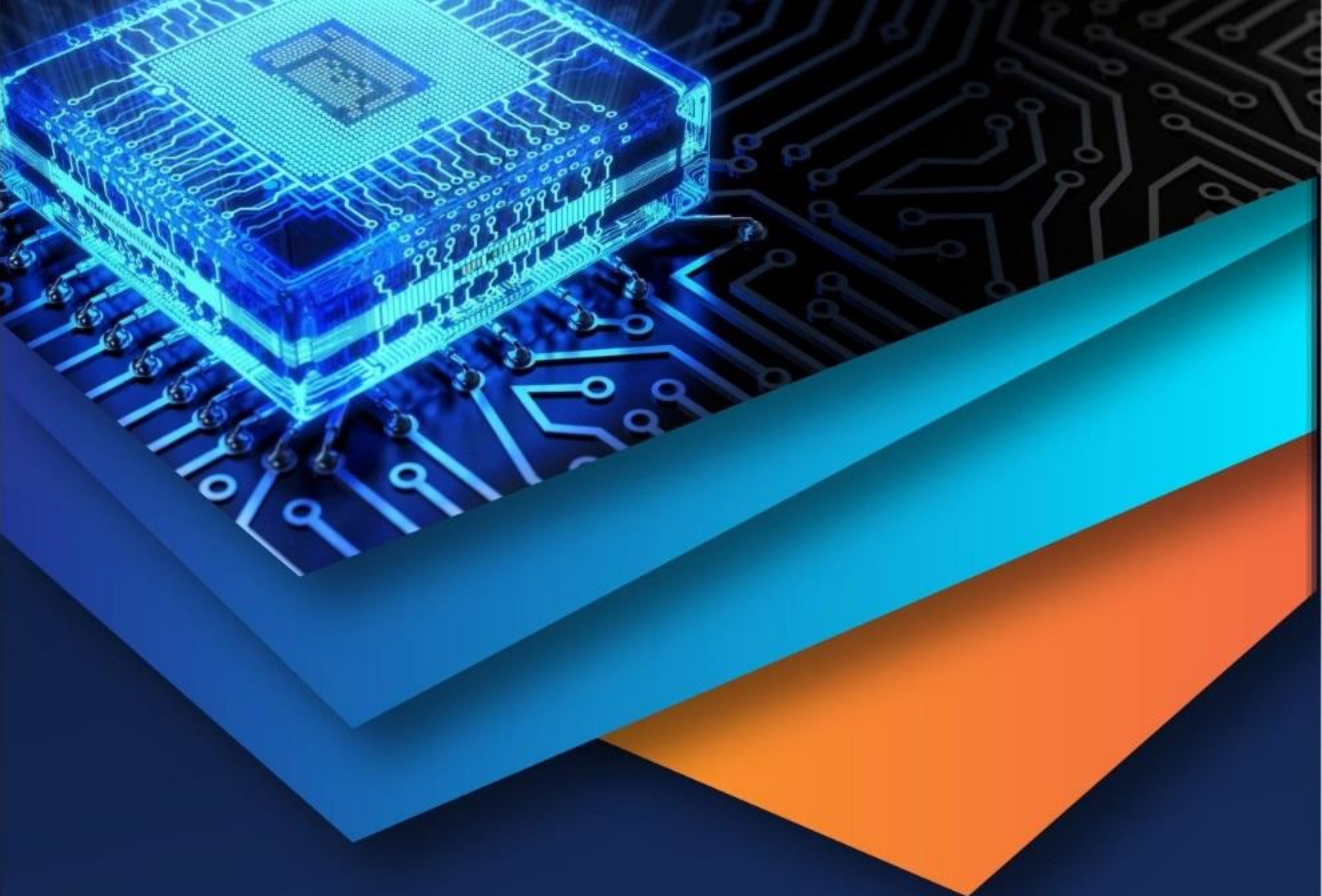

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