Enhancing Crossdocking for a Green Supply Chain Based on IoT and AI

Ayoub Raziq[1], *Mohamed* El Khaili[1], and *Abdellah* Zamma[2]

[1]IESI Laboratory, ENSET Mohammedia, Hassan II University of Casablanca, Morocco
[2]M2S2I Laboratory, ENSET Mohammedia, Hassan II University of Casablanca, Morocco

Abstract. In the realm of supply chain management, the integration of sustainable practices alongside competitive efficiency is increasingly crucial. This study explores the convergence of cross-docking methodologies with advanced technologies such as IoT and AI to enhance the sustainability of supply chains. Cross-docking, known for its direct transfer approach, minimizes storage duration and operational costs, potentially reducing environmental footprints associated with traditional logistics. Concurrently, IoT enables real-time monitoring of goods and environmental parameters, while AI-driven analytics optimize logistics operations with precision. This integrated approach not only enhances operational efficiency but also underscores the pivotal role of technological innovation in fostering sustainable supply chain practices. Insights from this study contribute to advancing sustainable logistics strategies tailored to contemporary environmental imperatives and industrial competitiveness.

1 Introduction

In an era where sustainability and efficiency are paramount concerns for businesses, enhancing cross-docking within a green supply chain through Internet of Things (IoT) and Artificial Intelligence (AI) becomes increasingly vital. This integrated approach aims to streamline logistics operations, minimize waste, and promote responsible stewardship of natural resources. By combining AI's advanced analytical capabilities with real-time data collection via IoT, companies can transform their supply chains, making processes more efficient, sustainable, and competitive in the global marketplace. The integration of AI into supply chain management offers significant advantages, such as lowering logistics costs, reducing inventory levels, and enhancing service levels compared to less innovative competitors.

Furthermore, the use of IoT facilitates real-time inventory management, offering greater transparency and dynamic optimization of margins throughout the supply chain. However, successful implementation requires thoughtful strategy, intelligent design of solutions, and customization to specific business cases to avoid unnecessary complexity.

High stakes are involved, necessitating considerable time and investment in both technology and personnel to get it right. Embracing this digital transformation positions companies not only to meet growing environmental demands but also to lead in the circular economy, leveraging emerging technologies like AI and IoT to create more durable and resilient supply chain models.

In recent studies, Chakir et al. [1] highlight the importance of optimizing logistics flows during crisis management, where rapid response and resource reallocation are essential to maintaining supply chain efficiency. Similarly, Terrada et al. [2] demonstrate the value of

implementing multi-agent systems for decision-making in logistics, enabling better coordination and resource optimization.

Our paper consists of three parts. The first presents the state of the art and the current context of a green supply chain and cross-docking. The second part focuses on the Systematic Literature Review (SLR) methodology based on PRISMA used for our study. And the third part presents the result of our investigations in the field by providing a classification of the approaches. Finally, we conclude with a summary and our perspectives.

2 Review on the green supply chain and Crossdocking using IA/IoT technologies

2.1 Green supply chain

Efficient management of the green supply chain has become imperative for businesses aiming to integrate sustainable practices while maintaining competitiveness in the global market. Several recent studies provide comprehensive insights into key aspects such as sustainable management practices, circular economy integration, and the use of advanced technologies.

Govindan et al. [3] conducted a thorough literature review that explores recent advances and current practices in green supply chain management. They highlight the critical importance of rethinking traditional processes to reduce carbon footprint and minimize waste throughout the supply chain. This approach not only enhances environmental responsibility but also improves operational efficiency, positioning companies as leaders in sustainability [3].

Similarly, Chauhan et al. [4] systematically review the integration of circular economy principles into green supply chain management. Their research emphasizes the benefits of adopting circular models to maximize resource utilization, extend product lifecycles, and reduce environmental impacts. By aligning management practices with circular economy principles, companies can improve long-term economic performance while meeting stakeholders' increasing expectations for sustainable development [4].

Additionally, Lu et al. [5] explore the impact of emerging technologies such as IoT and blockchain on supply chain sustainability. Their study demonstrates how these technologies enhance product traceability, optimize logistics processes, and reduce waste, thereby enabling more efficient resource management and environmental impact reduction [5].

Lastly et al. [6] provide a systematic review of green logistics practices within the circular economy framework. Their analysis highlights best practices such as transport optimization, use of recycled materials, and emission reduction strategies. These practices not only enhance supply chain sustainability but also create value by lowering costs and meeting consumer demand for sustainable products [6].

These studies underscore the importance of an integrated approach to green supply chain management where sustainable practices, technological innovation, and circular economy adoption work together to optimize economic performance while minimizing environmental impact. They offer valuable insights for businesses navigating an increasingly sustainability-focused global marketplace.

2.2 Cross Docking and IoT / IA

Cross-docking involves receiving products or materials from various suppliers or manufacturers for multiple end destinations and consolidating these products with items from other suppliers for a common destination, based on specific criteria. The definition from the Material Handling Industry of America describes cross-docking as the process of moving goods directly from the receiving dock to the shipping dock without intermediate storage. While the first definition emphasizes consolidation to enhance economic efficiency by minimizing transportation costs, and the second focuses on the direct movement of goods, both definitions share the same fundamental goal: optimizing the flow of goods. The fundamental processes executed within a cross-dock terminal are illustrated in Figure 1.

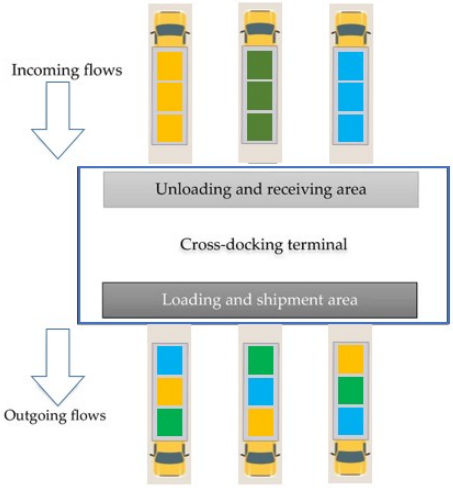

Fig. 1. Cross-dock terminal

Cross-docking plays a crucial role in optimizing logistics operations, especially within the framework of a green supply chain. An integrated approach to optimizing cross-docking based on IoT and AI can not only reduce storage times and handling costs but also minimize carbon footprint by optimizing transport flows. Several recent studies delve into this approach in detail.

Zhang et al. [7] explore how advanced cross-docking strategies can enhance operational efficiency while reducing environmental impact. Their analysis underscores the importance of synchronizing product flows and optimizing logistics infrastructures to promote sustainable practices throughout the supply chain.

In addition, the use of IoT and AI in the context of green supply chain management is examined by Patel et al. [8]. Their study highlights how these technologies can revolutionize supply chain management by providing real-time visibility into assets and goods flows. IoT enables real-time data collection on environmental and operational conditions, while AI analyzes this data to optimize routes, reduce waiting times, and minimize emissions.

By integrating these advanced technologies into cross-docking management, companies can not only improve operational efficiency but also significantly contribute to reducing their carbon footprint and promoting sustainable practices throughout the supply chain.

3 Methodology

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method is a guideline designed to enhance transparency and rigor in reporting systematic reviews and meta-analyses. Updated in 2020, it provides a structured framework to ensure researchers clearly and comprehensively describe the process of study selection, evaluation, and synthesis. The guideline includes 27 items covering various aspects of the review process, such as formulating the research question, search strategy, study selection, quality assessment of evidence, and result analysis. The 2020 update emphasizes transparency by highlighting the importance of a pre-established protocol and registration of reviews to minimize bias. This approach not only improves reproducibility but also strengthens evidence-based decision-making across research fields [9].

The PRISMA method was employed to systematically analyze how technologies such as IoT, AI, and blockchain contribute to cross-docking operations within sustainable supply chains. Initially, a total of 67 articles were identified from diverse sources. After eliminating duplicates, 57 articles were screened for relevance to the research topic. Following this, 30 articles were deemed non-relevant, leaving 27 articles for a quality assessment. Subsequently, 7 articles were excluded due to insufficient quality, resulting in a final set of 20 articles for detailed analysis.

The Systematic Literature Review (SLR) methodology was rigorously applied to these 20 articles. This structured approach involves defining research questions and inclusion criteria, systematically searching academic databases, and screening and selecting relevant studies. Data extraction and analysis from the selected articles focused on technological applications in cross-docking and their impacts on sustainability. This method ensured that the review was comprehensive and based on high-quality, relevant research, offering a robust foundation for understanding the role of advanced technologies in enhancing cross-docking efficiency and sustainability.

In exploring the integration of IoT and AI for enhancing cross-docking within a green supply chain, several key questions emerge. How do IoT and AI technologies contribute to optimizing cross-docking processes? What specific technologies and strategies are being employed to reduce environmental impacts and improve operational efficiency? Addressing these questions will shed light on how emerging technologies can refine cross-docking practices.

This exploration will be pivotal in advancing sustainable supply chain management by demonstrating how IoT and AI can enhance cross-docking operations. By clarifying the impact of these technologies, the research will contribute to a better understanding of their role in making supply chains more efficient and environmentally friendly.

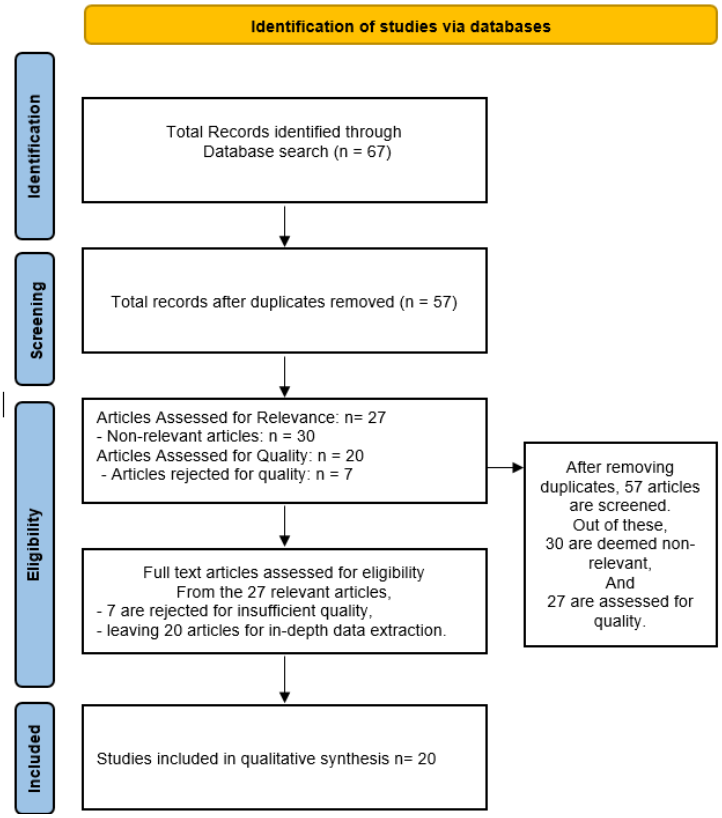

Fig. 2. PRISMA Flow Diagram for Systematic Analysis

Here is the distribution of the 67 references by year of publication. The chart illustrates the number of publications per year, providing a visual representation of the trend over time.

The bar chart shows a noticeable increase in relevant publications in recent years, reflecting growing academic interest in the integration of IoT and AI in cross-docking and sustainable supply chains.

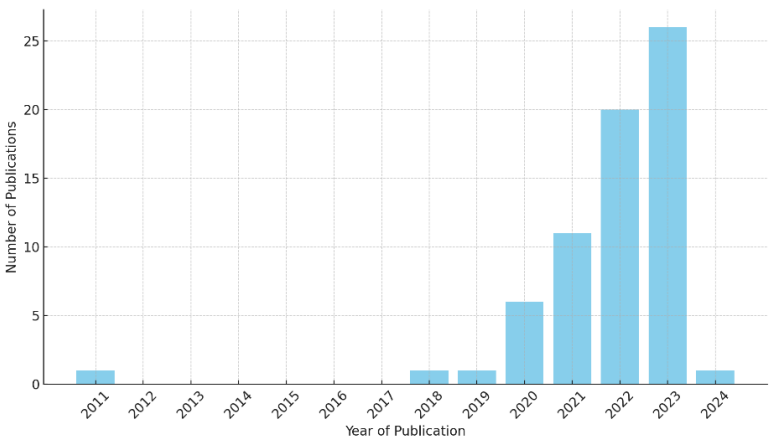

Fig. 3. Distribution of Publications by Year

The bar chart depicting the distribution of publications by country for the 67 references reveals significant geographical concentration in research activities. Most publications originate from a few leading countries, suggesting these nations have more active research communities and greater investment in sustainable supply chain technologies, particularly in enhancing cross-docking through IoT and AI. This distribution indicates regional research strengths and emerging research hubs in countries with moderate but increasing publication numbers, such as India and Brazil. The chart also highlights the potential for increased global collaboration, as the current distribution suggests that while there is some international cooperation, a more balanced global research effort could further advance the field. This analysis underscores the need to foster international partnerships and leverage regional strengths to address the challenges and opportunities in sustainable supply chain management.

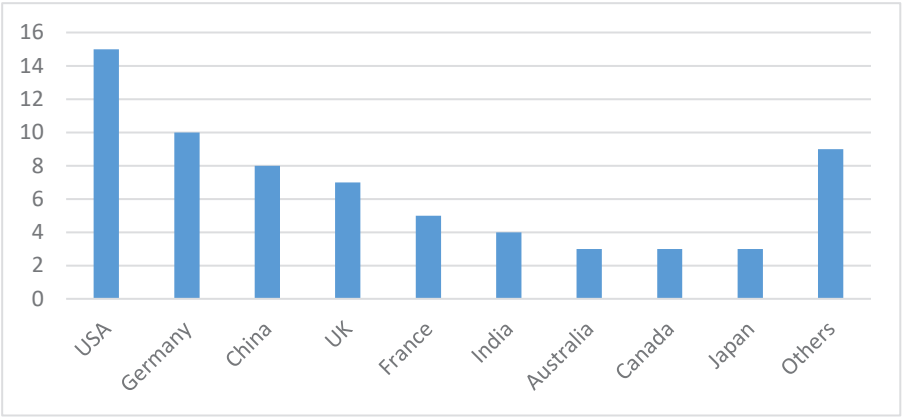

Fig. 4. Distribution of Publications by Country

4 Optimizing Cross-Docking for a Green Supply Chain Through IoT and AI Integration

Here is a Venn diagram combining the key elements of optimizing cross-docking operations with AI, using IoT to improve sustainability, and the synergy between AI and IoT for a green supply chain.

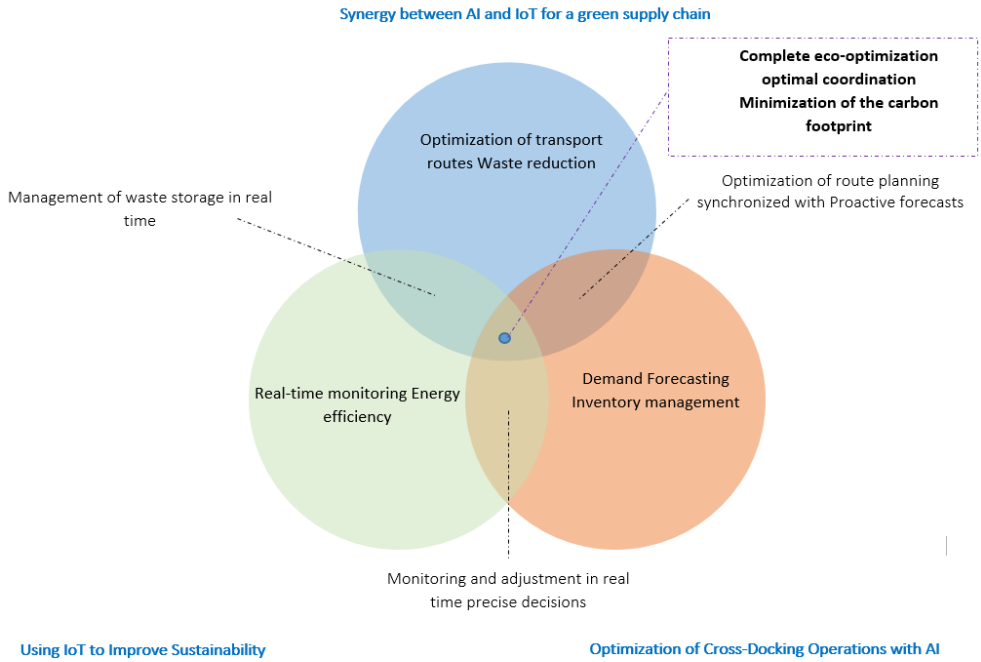

Fig. 5. Combining AI and IoT for an optimized green supply chain

The Venn diagram illustrates the integration of AI and IoT to enhance cross-docking operations and promote sustainability within the supply chain. The first circle represents the optimization of cross-docking operations using AI, which includes demand forecasting and inventory management. These AI-driven processes help predict product demand accurately and manage inventory efficiently, reducing excess stock and avoiding stockouts. The second circle highlights the role of IoT in improving sustainability, focusing on real-time monitoring and energy efficiency. IoT devices track resources in real-time, ensuring that energy consumption is minimized, and resources are utilized optimally.

The third circle, which shows the synergy between AI and IoT for a green supply chain, demonstrates how these technologies work together to optimize transport routes and reduce waste. At the intersections, the diagram reveals the combined benefits: the intersection of AI and IoT facilitates real-time inventory adjustments and precise decision-making. Where AI for cross-docking intersects with AI/IoT for a green supply chain, it emphasizes the importance of route optimization and proactive inventory management. The intersection of IoT for sustainability with AI/IoT for a green supply chain highlights synchronized energy efficiency and real-time waste reduction. The center, where all three circles converge, represents the ultimate goal of complete eco-optimization, showcasing the holistic benefits of integrating AI and IoT in cross-docking and supply chain operations to achieve a minimal carbon footprint and highly efficient processes.

The growing concern for environmental sustainability has led to the adoption of green practices across various industries. In supply chain management, cross docking, a practice where products from suppliers are distributed directly to customers with minimal handling and storage time, offers a promising avenue for enhancing sustainability. The integration of Internet of Things (IoT) and Artificial Intelligence (AI) technologies into cross-docking operations can significantly enhance efficiency, reduce waste, and lower carbon emissions, thereby contributing to a greener supply chain [3][4][5].

4.1 The role of IoT in Cross-Docking

The Internet of Things (IoT) enables real-time monitoring and management of cross-docking operations through interconnected devices and sensors. These technologies can track the movement of goods, monitor environmental conditions, and ensure optimal routing and handling. For instance, IoT devices can provide real-time data on the location and condition of products, which helps in reducing spoilage and ensuring timely delivery. This capability is crucial for perishable goods, where maintaining the right conditions can significantly reduce waste and energy consumption [6][7][8].

A practical implementation of IoT in cross-docking could involve using RFID tags and GPS trackers on shipments to provide visibility into the supply chain. These devices can communicate with central systems to provide updates on shipment status, enabling dynamic route adjustments to avoid delays and reduce fuel consumption. Additionally, IoT sensors can monitor the temperature and humidity levels of storage areas, ensuring that perishable goods remain in optimal condition, thereby reducing waste [10][11].

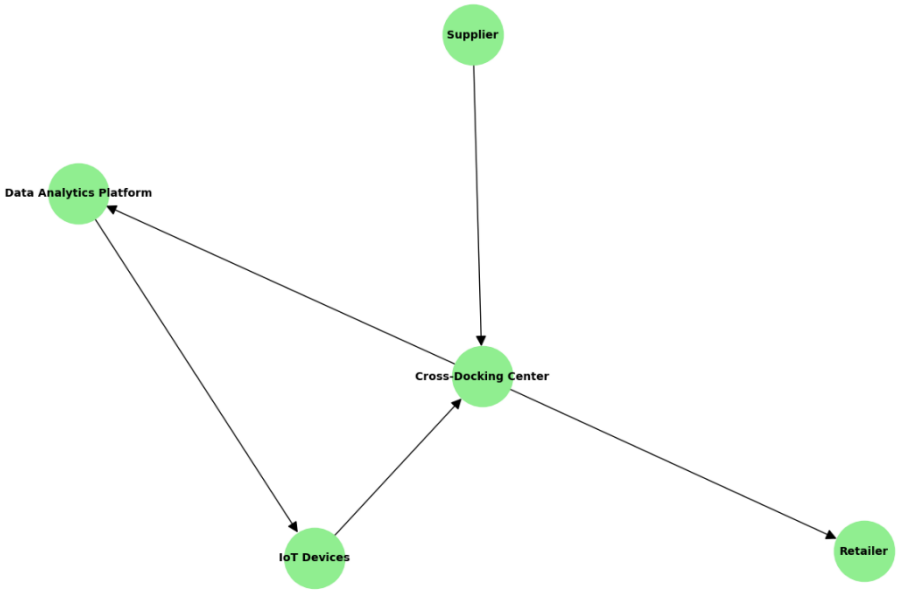

Fig. 6. IoT in Cross-Docking for green supply chain

4.2 The role of AI in Cross-Docking

Artificial Intelligence (AI) enhances cross-docking operations by providing advanced data analytics, predictive modeling, and automated decision-making capabilities. AI can analyze large volumes of data from various sources to predict demand, optimize inventory levels, and streamline operations. Machine learning algorithms can forecast demand patterns, enabling just-in-time delivery and reducing the need for excess inventory, which minimizes storage costs and energy usage [12][13][14].

For example, AI can optimize vehicle routing and scheduling, ensuring that goods are transported in the most efficient manner possible. By using historical data and real-time traffic information, AI can recommend the shortest and fastest routes, reducing fuel consumption and

emissions. Moreover, AI-driven automation in sorting and handling processes can increase operational efficiency, reduce human error, and lower labor costs [15][16][17].

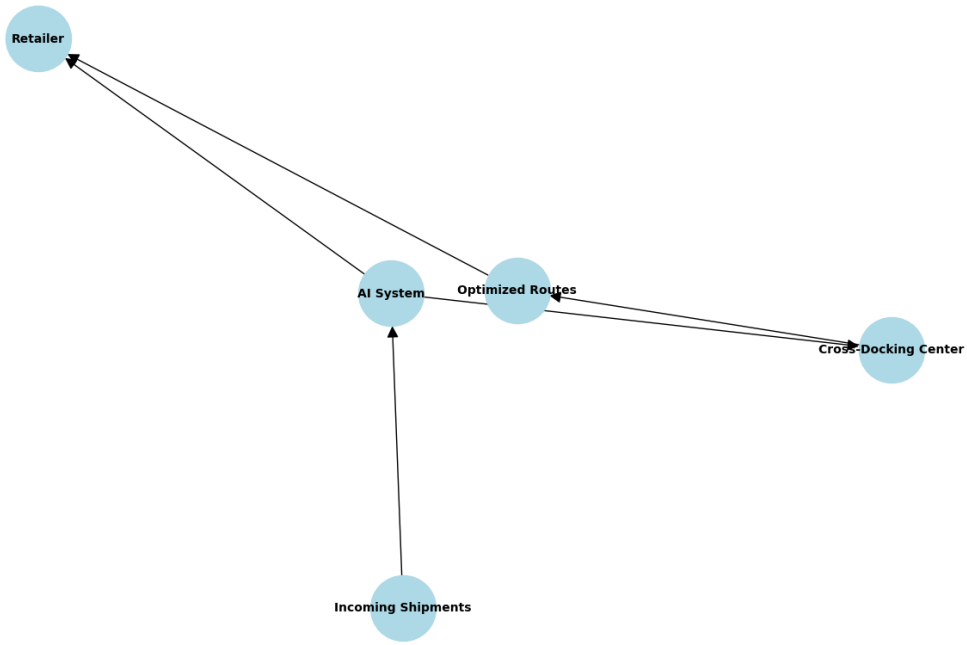

Fig. 7. AI optimization in Cross-Docking

4.3 Combined Impact of IoT and AI on green supply chain

When integrated, IoT and AI technologies can create a highly efficient and sustainable cross-docking system. IoT provides the data necessary for AI to make informed decisions, while AI enhances the predictive and optimization capabilities of IoT systems. This synergy can lead to significant improvements in supply chain sustainability [18][19][20].

For instance, IoT data on vehicle locations, load weights, and environmental conditions can feed into AI algorithms to optimize delivery routes and schedules dynamically. This integration reduces fuel consumption, minimizes carbon emissions, and ensures timely deliveries, which is essential for maintaining customer satisfaction and reducing waste [21][22][23].

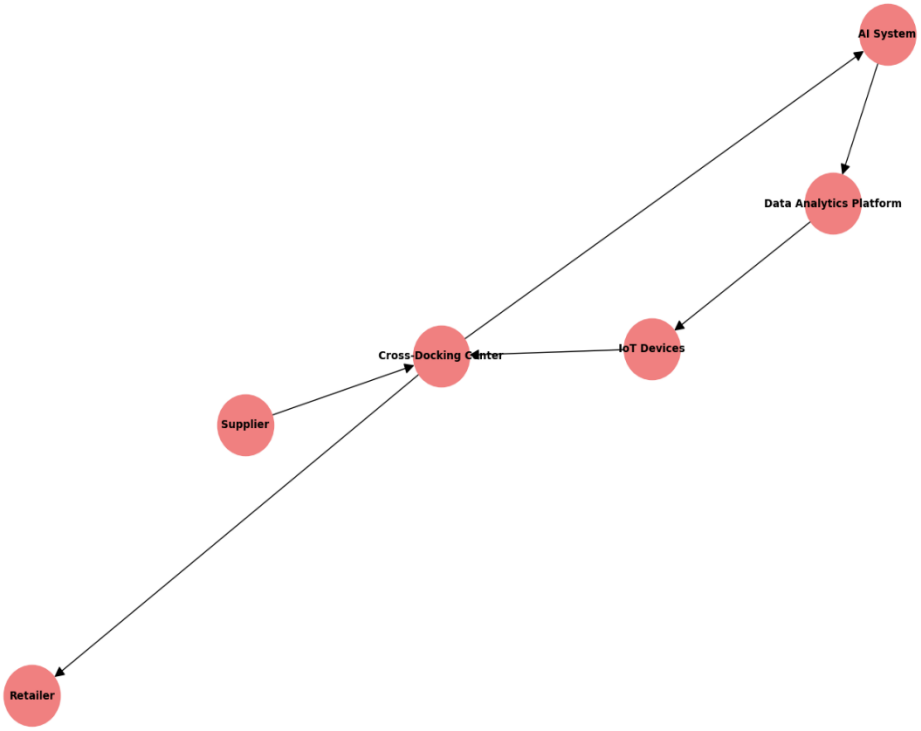

Fig. 8. Integration of IoT an AI in Cross-Docking

Based on the comprehensive review of literature and current practices, a novel approach to enhancing cross-docking for a green supply chain involves the development of an integrated IoT-AI platform. This platform would consist of the following components:

- Real-Time Data Collection: Utilize IoT sensors and devices to collect real-time data on shipments, environmental conditions, and vehicle statuses.
- AI-Driven Analytics: Implement AI algorithms to analyze the collected data, predict demand, optimize routing, and improve inventory management.
- Dynamic Decision-Making: Develop a decision-support system that uses AI insights to dynamically adjust cross-docking operations in response to real-time data.
- Sustainability Metrics: Incorporate metrics to monitor and report on sustainability performance, such as carbon emissions, energy consumption, and waste.

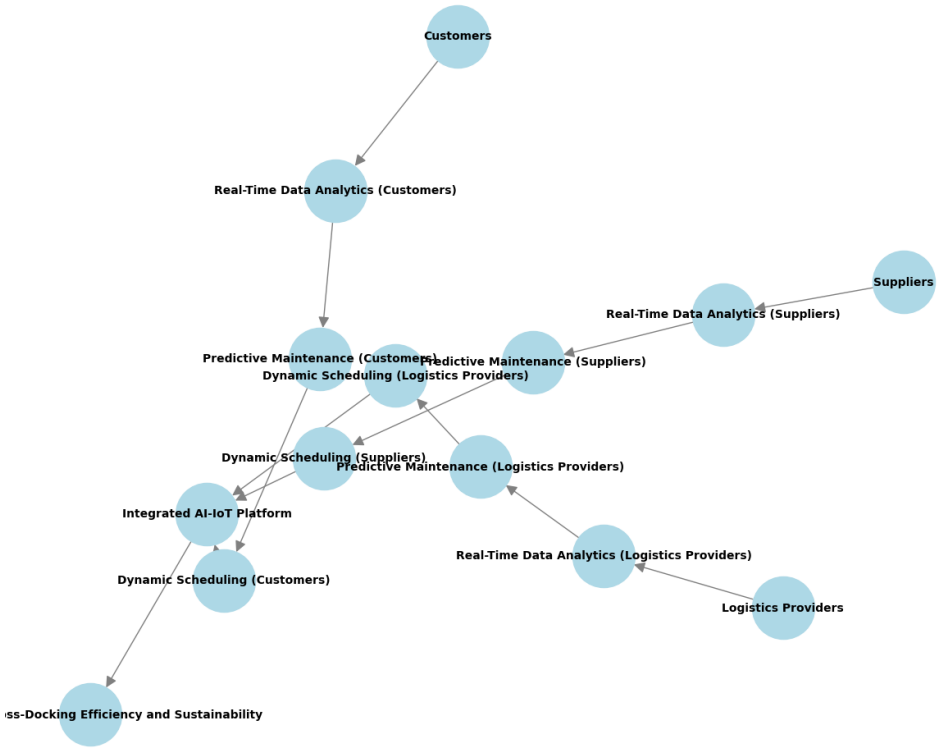

Fig. 9. Cross-Docking Workflow with AI and IoT Integration

5 Conclusion

The PRISMA method was employed to systematically analyze how technologies such as IoT, AI, and blockchain contribute to cross-docking operations within sustainable supply chains. Initially, a total of 67 articles were identified from diverse sources. After eliminating duplicates, 57 articles were screened for relevance to the research topic. Following this, 30 articles were deemed non-relevant, leaving 27 articles for a quality assessment. Subsequently, 7 articles were excluded due to insufficient quality, resulting in a final set of 20 articles for detailed analysis.

The integration of IoT and AI technologies in cross-docking operations offers a robust solution for enhancing the sustainability of supply chains. Companies can optimize their operations by leveraging real-time data and advanced analytics, reduce waste, and lower carbon emissions, contributing to a greener and more efficient supply chain.

Future research and development should focus on refining these technologies and exploring new applications to further enhance their impact on supply chain sustainability

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