



# Green Logistics with Interdisciplinary Approaches

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# GREEN LOGISTICS WITH INTERDISCIPLINARY APPROACHES

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## PREFACE

As the volume and complexity of global trade expand, the logistics sector has emerged not only as the engine of economic growth but also as the most critical front in environmental sustainability. Today, “Green Logistics” represents a multidimensional paradigm shift that transcends traditional cost-minimization approaches, integrating ecological balance, social welfare, and technological innovation into a common framework.

This volume, titled “**Green Logistics with Interdisciplinary Approaches**”, aims to redefine green logistics through a rigorous interdisciplinary lens. The opening chapters establish the theoretical framework, transitioning from environmental impacts to sustainable transformation, while meticulously examining the global policies and practices that shape this evolution. Subsequent chapters analyze the financial implications and investment costs of this transition, providing the strategic foundations necessary for process optimization and efficiency analysis in logistics.

A significant portion of the work explores the technological frontier, addressing how artificial intelligence, smart systems, and big data analytics transform decision-making processes and elevate sustainability performance across logistics networks. The final section concludes the green logistics cycle by examining transportation infrastructure from an engineering perspective, specifically focusing on highway-railway systems and sustainable pavement materials.

Compiled with contributions from distinguished scholars across various disciplines, we hope this book serves as a roadmap for academics, policymakers, and logistics professionals, fostering new academic discourse toward a sustainable future.

*“Türkiye, at the heart of logistics, charts the course for tomorrow through green transformation: From the crossroads of continents to the center of a sustainable future!”*

*Assoc. Prof. Kürşat YILDIZ<sup>1</sup>*

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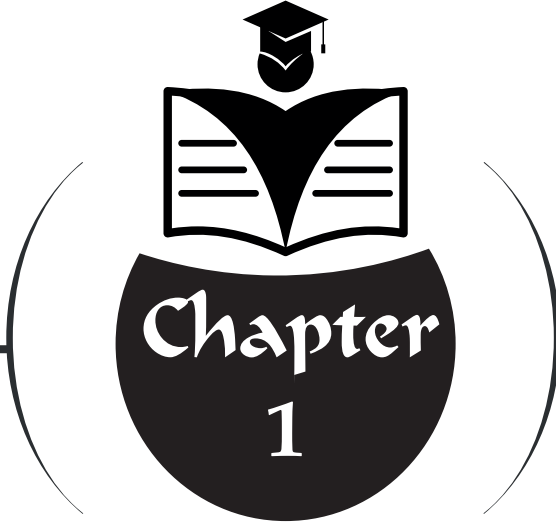
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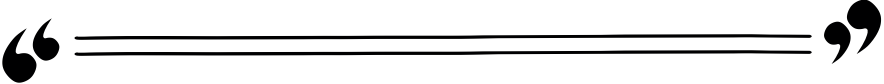
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## **GREEN LOGISTICS: FROM ENVIRONMENTAL IMPACTS TO SUSTAINABLE TRANSFORMATION**



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## **Introduction**

Global climate change, accelerating resource depletion, and increasing environmental degradation have necessitated a fundamental reassessment of production and consumption systems worldwide. This transformation extends beyond environmental policy, directly influencing economic structures, supply chains, and logistics systems that underpin the global economy. Within this context, the sustainable development paradigm has emerged as a multidimensional framework integrating environmental, economic, and social objectives, positioning the logistics sector at the center of sustainability transitions due to its significant environmental footprint.

As a backbone of global trade and economic growth, logistics systems generate substantial environmental pressures through energy consumption, greenhouse gas emissions, natural resource use, waste production, and land-use change. The expansion of global trade, rapid urbanization, the growth of e-commerce, and increasingly extended supply chains have further intensified these impacts, revealing the limitations of traditional logistics models primarily driven by speed and cost efficiency.

In response to international environmental policies, climate mitigation strategies, and the United Nations Sustainable Development Goals (SDGs), the concept of green logistics has emerged as a comprehensive approach aimed at reducing the environmental impacts of logistics systems. Rather than focusing solely on environmentally friendly transportation, green logistics represents a systemic transformation encompassing energy efficiency, emissions management, sustainable operations, and environmentally responsible logistics planning.

This chapter examines the environmental impacts of logistics from a multidimensional perspective and analyzes the conceptual foundations, historical evolution, and implementation dimensions of green logistics within an integrated framework. By synthesizing existing literature, the chapter aims to provide a comprehensive conceptual basis for understanding environmental sustainability in logistics and to contribute to ongoing academic discussions on sustainable logistics transformation.

### **1. The Need for Green Logistics**

Global climate change, accelerating resource depletion, and increasing environmental degradation have transformed sustainability from an environmental concern into a structural challenge affecting production, consumption, and governance systems. Within this transformation, logistics occupies a critical position due to its role in facilitating global trade and enabling the movement of goods and services across increasingly complex supply chains.

Empirical studies demonstrate that logistics activities generate substantial environmental pressures through energy consumption, greenhouse gas emissions, and intensive resource use, further intensified by expanding trade volumes, rapid urbanization, and the growth of e-commerce (United Nations Conference on Trade and Development, 2024; Viu-Roig & Alvarez-Palau, 2020). Traditional logistics systems, historically driven by speed and cost efficiency, have therefore proven insufficient in addressing emerging environmental and climate-related risks.

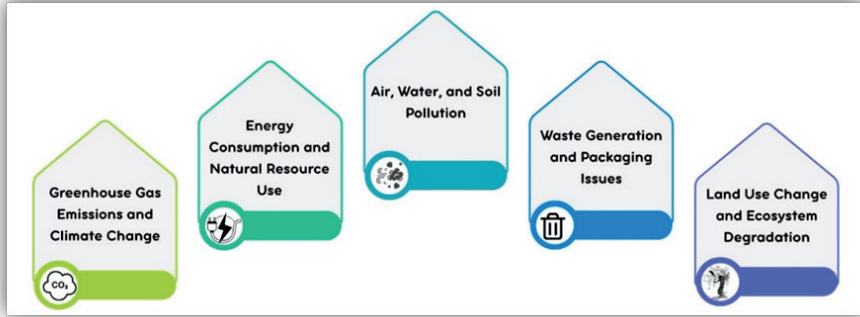
International environmental agreements, climate mitigation policies, and the United Nations Sustainable Development Goals (SDGs) have positioned sustainability as a central driver of logistics transformation. In this context, green logistics has emerged as a holistic framework integrating environmental considerations into both operational and strategic logistics decisions. Beyond incremental environmental improvements, green logistics represents a systemic transition aimed at reducing environmental pressures while supporting long-term economic and social sustainability (Garg & Vemaraju, 2025; Rastegardebidi & Su, 2025).

This chapter contributes to the literature by integrating environmental impact assessment, operational logistics practices, and spatial planning perspectives into a unified conceptual framework for green logistics transformation.

## **2. Environmental Impacts of the Logistics Sector**

The logistics sector plays a central role in the functioning of global production and consumption systems and occupies a strategic position within both economic and social structures. However, it is also recognized as one of the sectors exerting the highest levels of environmental pressure. International reports and academic studies indicate that logistics activities generate direct and indirect impacts across multiple environmental indicators, including natural resource depletion, greenhouse gas emissions, energy consumption, air and noise pollution, waste generation, and fossil fuel dependency (Cheng et al., 2024; Rehman Khan et al., 2018).

The environmental effects arising at each stage of logistics operations accumulate over time, contributing to the expansion of the sector's overall environmental footprint. Therefore, a comprehensive assessment of the environmental impacts of logistics is essential for the formulation of sustainable development policies and for establishing a robust foundation for green logistics practices. Figure 1 illustrates the major categories of environmental impacts associated with the logistics sector.



*Figure 1 Major Types of Environmental Impacts in the Logistics Sector*

*Source: Author's own elaboration based on relevant literature.*

Figure 1 presents a holistic framework of the principal environmental impact categories generated by logistics activities, synthesized from the relevant academic literature. These impact domains are classified under the following headings: greenhouse gas emissions and climate change; energy consumption and natural resource use; air–water–soil pollution; waste generation and packaging-related issues; and land-use change and ecosystem degradation.

This classification underscores that the environmental impacts of logistics are not confined to a single dimension; rather, they exhibit a multidimensional and interconnected structure. Accordingly, each impact domain is examined in detail under separate subsections, taking into account the operational characteristics and structural dynamics of the logistics sector.

### **2.1. Greenhouse Gas Emissions and Climate Change**

The uncontrolled increase in greenhouse gas (GHG) emissions is widely recognized as a primary driver of climate change, contributing to rising global temperatures and structural alterations in the climate system (IPCC, 2022). Within logistics systems, GHG emissions represent one of the most measurable environmental impact domains, with transportation, warehousing, and distribution activities identified as major emission sources (Kallionpää et al., 2026).

According to the IPCC (2022), the transport sector accounts for approximately 15% of global energy-related greenhouse gas emissions, with carbon dioxide (CO<sub>2</sub>) as the dominant component. Emissions largely originate from fossil fuel combustion across road, maritime, air, and rail transport modes. The International Energy Agency (IEA, 2023) reports a steady increase in transport-related CO<sub>2</sub> emissions over the past decade, driven primarily by freight transportation growth.

Among transport modes, road freight transport produces the largest share of logistics-related emissions due to its reliance on diesel fuel (Rastegardebidi & Su, 2025). Maritime transport, while more energy-efficient per unit of cargo, contributes significantly to global emissions because of the scale of international trade, accounting for approximately 2.7–3% of total emissions (Fadaie et al., 2025). Air transport exhibits the highest emission intensity per ton-kilometer, whereas rail transport generates comparatively lower—yet still notable—emissions (Ayvaz, 2025).

Beyond transportation, warehousing operations increasingly contribute to logistics-related emissions through electricity consumption, heating and cooling systems, and material-handling equipment. Consequently, greenhouse gas emissions across transportation and storage processes position the logistics sector as a significant driver of climate change.

Reducing emissions through energy-efficient practices, low-carbon technologies, and decreased fossil fuel dependency has therefore become a strategic priority for green logistics implementation. Since emission levels are closely linked to energy consumption and resource use patterns, the following subsection examines energy consumption and resource utilization within the logistics sector.

## ***2.2. Energy Consumption and Natural Resource Use***

Core logistics—including transportation, warehousing, handling, and distribution—are characterized by high energy intensity. The sector's reliance on fossil fuels contributes not only to greenhouse gas emissions but also to the depletion of non-renewable resources (Yan, 2026), extending environmental impacts beyond carbon emissions to broader ecological pressures.

Logistics systems also require intensive use of materials and natural resources. Energy inputs for electricity generation, packaging materials such as paper, plastics, and metals, and land, water, and construction materials used in logistics infrastructure constitute major resource demands. The widespread use of single-use packaging further reduces resource efficiency as logistics networks expand spatially.

Large logistics facilities consume substantial energy for lighting, climate control, automation, and digital infrastructure. Cold storage and refrigerated transport systems intensify environmental pressures due to high electricity demand and refrigerants with elevated global warming potential (Long & Liu, 2025). These dynamics collectively create a multidimensional ecological footprint extending beyond energy-related impacts.

According to the International Energy Agency, the transport sector accounts for nearly 30% of global final energy consumption, largely dependent on fossil fuels. Consequently, logistics represents a strategic risk domain not

only for climate mitigation but also for long-term energy security and resource management. These energy and resource pressures also contribute to various forms of environmental pollution, examined in the following section.

### 2.3. Air, Water, and Soil Pollution

Logistics activities generate multidimensional pollution impacts that extend beyond greenhouse gas emissions, simultaneously affecting air, water, and soil systems. Emissions from transport operations release pollutants such as nitrogen oxides, sulfur dioxide, particulate matter, and carbon monoxide, contributing significantly to urban air quality deterioration and associated public health risks (Kováčiková et al., 2024; WHO, 2021).

Maritime and logistics facility operations may also lead to water contamination through fuel spills, chemical leakage, and ballast water discharge, posing risks to aquatic ecosystems and freshwater resources (OECD, 2021; IMO, 2020). Similarly, fuel and chemical leakages in logistics centers and terminals contribute to long-term soil degradation, negatively affecting vegetation, agricultural productivity, and ecosystem stability (Alengebawy et al., 2021).

Together, these pollution pathways demonstrate that logistics-related environmental impacts operate as interconnected ecological pressures requiring integrated mitigation strategies within the green logistics framework.

### 2.4. Waste Generation and Packaging Challenges

Logistics activities—including warehousing, distribution, transportation, and reverse logistics—generate substantial quantities of solid and packaging-related waste throughout supply chain operations (Popescu et al., 2024). Materials used to protect, transport, and track products—particularly single-use plastics, cardboard, pallets, and stretch films—constitute major contributors to the sector’s environmental footprint.



Figure 2. Major Daily Waste Outputs of the Logistics Sector.  
Source: Author’s own elaboration based on relevant literature.

Figure 2 categorizes the principal waste streams generated by daily logistics operations into three groups: packaging-related waste; waste arising from reverse logistics and return processes; and operational waste associated with warehousing activities. This classification demonstrates that waste generation in logistics is a continuous, multi-stage process extending beyond product flows alone.

Beyond disposal and management challenges, increasing waste volumes also expand spatial requirements for storage and separation facilities, thereby intensifying pressures on land use and natural ecosystems.

### 2.5. Land Use and Ecosystem Pressures

The expansion of the logistics sector has increased demand for large-scale operational areas, leading to significant land-use transformations and heightened pressure on natural ecosystems (Chen et al., 2023). Logistics facilities typically require extensive, flat land areas, which often results in the conversion of agricultural lands, forests, and open-green spaces when deemed spatially suitable for investment.

When ecological sensitivities are insufficiently considered, such conversions result in habitat loss, ecosystem fragmentation, and biodiversity decline, producing long-term environmental degradation that is often difficult to reverse (OECD, 2021; EEA, 2022).

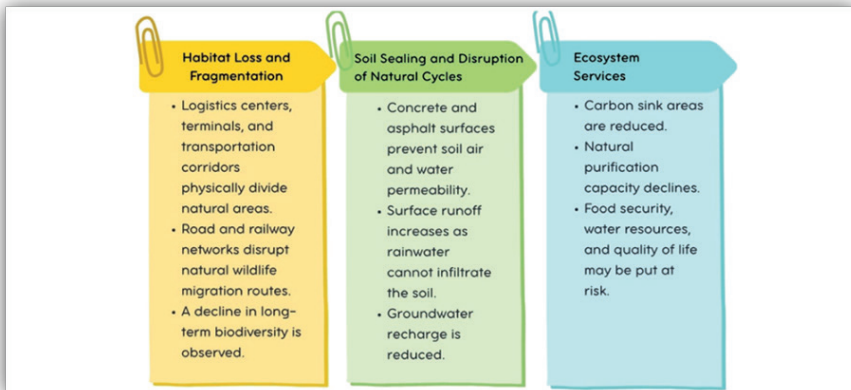


Figure 3. Impacts of Logistics Centers and Transport Corridors on Natural Areas.

Source: Author's own elaboration based on relevant literature.

Figure 3 summarizes the environmental impacts of logistics centers, terminals, and transport corridors on natural areas, categorizing them under habitat loss and fragmentation, surface sealing and disruption of natural cycles, and reductions in ecosystem services. These relationships demonstrate

that logistics infrastructure exerts multidimensional pressures not only on physical landscapes but also on biodiversity, water cycles, and carbon sequestration systems.

Overall, greenhouse gas emissions, energy and resource use, air–water–soil pollution, waste generation, packaging challenges, and land-use pressures collectively reveal that the current structure of the logistics sector entails interconnected and multidimensional sustainability challenges. Logistics activities contribute not only to global climate change but also generate persistent environmental pressures at local and regional scales, affecting natural resources, ecosystems, and quality of life. The continuation of high-carbon and resource-intensive logistics systems risks deepening these pressures and amplifying environmental risks.

Accordingly, the adoption of new approaches aimed at reducing environmental impacts, improving resource efficiency, and limiting ecosystem pressures has become imperative. The green logistics paradigm, which provides both the conceptual and practical foundation for this transformation, is examined in the following section.

### **3. Green Logistics**

#### ***3.1. Historical Development and Conceptual Framework***

The emergence and evolution of green logistics have been widely discussed in the literature across different historical periods. Although the roots of the concept can be traced back to the 1980s and 1990s, its systematic treatment as an integrated approach became more prominent after the early 2000s (Rodrigue et al., 2001a). This shift was closely linked to increasing awareness of the environmental impacts of logistics activities, particularly greenhouse gas emissions, energy consumption, resource use, and waste generation, which contributed to the formation of the theoretical foundations of green logistics.

Bibliometric and thematic analyses suggest that green logistics has followed a multi-stage development trajectory. Ma and Kim (2023) identify three phases: the emerging period (1993–2003), the slow growth period (2004–2014), and the rapid growth period (2015–2021), reflecting substantial growth in both the quantity and depth of academic research.

Historically, the concepts of “green” and “logistics” were initially treated as separate domains before gradually converging into an integrated framework. Logistics was traditionally viewed as a technical field focused on planning and controlling freight movement, whereas “green” represented a value-oriented perspective centered on environmental sustainability. The integration of these perspectives led to the emergence of green logistics as a holistic approach aimed at minimizing environmental impacts while improving resource efficiency (Rodrigue et al., 2001b).

In the early 2000s, green logistics was largely perceived as a supportive tool for incorporating environmental considerations into production and distribution systems. Today, however, it is recognized as a fundamental component of modern logistics and a strategic management paradigm rather than merely an environmental adjustment (Yao et al., 2026). The integration of environmental considerations into logistics decision-making reflects a broader shift toward operating within ecological limits.

Accordingly, green logistics contributes to climate change mitigation, improved resource efficiency, and reduced environmental risks. The following subsection examines the core components of the green logistics approach and how logistics activities are restructured within this framework.

### 3.2. Core Components of Green Logistics

As the impacts of global climate change become increasingly evident, the concept and implementation of green logistics have gained growing significance at the global level. To comprehensively evaluate the green logistics approach, this study examines the fundamental components of the green logistics system within a structured conceptual framework. In this regard, Tao (2001) classified green logistics into seven core components, a classification that has become widely referenced in the green logistics literature. Figure 4 schematically presents the fundamental components constituting the green logistics system.



Figure 4. Core Components of the Green Logistics System.

Source: Adapted by the author from Tao (2001).

Based on Tao's (2001) classification, Figure 4 illustrates the core elements of the green logistics system within an integrated framework. These components encompass a broad range of activities, extending from supply chain management to production and transportation, and from packaging and

distribution processes to waste material logistics. This structure demonstrates that green logistics is not limited to isolated operational improvements; rather, it represents a systematic and integrated approach encompassing all stages of the supply chain. Accordingly, the fundamental components of the green logistics system are discussed below under separate subsections, grounded in established classifications within the literature.

• *Green Supply Chain*

Green supply chain management refers to the systematic integration of environmental considerations into all processes spanning from production to final consumption (Dzikriansyah et al., 2023). This approach is fundamentally grounded in environmental sustainability principles. Conceptually, it can be defined as the structured incorporation of environmentally oriented practices into traditional supply chain systems through coordinated and integrated planning.

• *Green Production Logistics*

Green production logistics denotes a sustainability-oriented approach aimed at reducing the environmental impacts associated with logistics activities in the production phase (Adebayo, 2025). Within this framework, logistics operations are designed and implemented in accordance with principles of resource efficiency, energy conservation, emission reduction, and waste minimization.

• *Green Transport Logistics*

Green transport logistics focuses on minimizing the environmental impacts generated by transportation activities within logistics systems (Temizceri & Kara, 2024). It seeks to reduce greenhouse gas emissions, noise pollution, air pollution, and energy consumption associated with the delivery of goods and services to end users. Aligning transportation systems with climate change mitigation objectives constitutes the core orientation of green transport logistics.

• *Green Packaging*

Green packaging refers to the environmentally responsible design and management of packaging systems used for the transportation, protection, and storage of products within logistics processes (Wu et al., 2025). Key principles include the use of recyclable materials, reduction of packaging volume, and limitation of single-use packaging materials.

• *Green Distribution Process*

The green distribution process encompasses the planning and execution of distribution activities—from production sites to final consumption points—in accordance with environmental sustainability principles. This approach

provides a conceptual framework for conducting distribution operations in a manner that prioritizes energy efficiency and emission reduction.

• *Green Distribution Logistics*

Green distribution logistics concerns the strategic planning and management of distribution-related logistics activities—including transportation, warehousing, and delivery—within the framework of environmental sustainability objectives. While the green distribution process emphasizes operational implementation, green distribution logistics focuses on how these practices are organized, coordinated, and optimized within logistics systems.

• *Waste Material Logistics*

Waste material logistics refers to the systematic management of waste generated throughout production, consumption, and service processes, including source separation, collection, storage, transportation, recovery, and final disposal. The planning and coordination of these activities in accordance with environmental, economic, and regulatory requirements constitute an essential component of sustainable logistics systems.

The components discussed in this section—including green supply chain management, production logistics, transportation, packaging, distribution, and waste logistics—demonstrate that green logistics functions as an integrated system spanning all stages of the supply chain. Although each component targets specific environmental objectives, they operate as interdependent and complementary elements within a unified framework.

Accordingly, the following section examines the practical applications of the green logistics approach under the broader heading of green logistics practices.

**3.3. Green Logistics Activities**

The primary objective of green logistics activities is to reduce the environmental impacts of conventional logistics operations and to restructure logistics systems in accordance with sustainability principles. In the literature, green logistics is conceptualized as a transformation process in which environmental considerations are systematically integrated into logistics systems and is widely regarded as a key component of modern logistics paradigms (Seroka-Stolka & Ociepa-Kubicka, 2019). In this context, the term “green” refers to the incorporation of ecological considerations into logistics operations to ensure environmentally compatible planning and implementation.

Green logistics extends beyond environmentally friendly transportation

practices and represents an integrated system encompassing procurement, warehousing, packaging, digitalization, carbon management, and reverse logistics activities. Although these domains are categorized differently across studies, this chapter reorganizes them within a unified conceptual framework reflecting their interrelated structure.

To illustrate the systematic relationships among green logistics activities, a conceptual model is developed and presented in Figure 5.

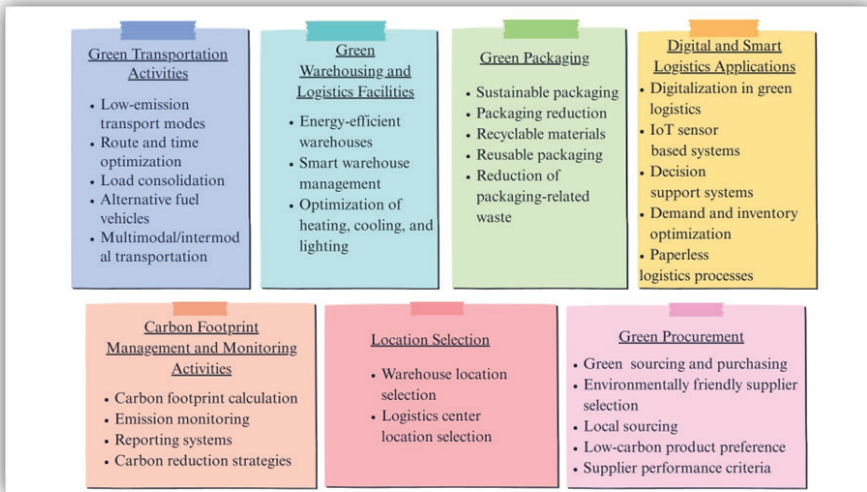


Figure 5. Conceptual Framework of Green Logistics Activities.

Source: Author’s own elaboration based on relevant literature.

Figure 5 presents green logistics activities within a holistic framework, including transportation, warehousing, packaging, digitalization, carbon footprint management, site selection, and green procurement. These domains represent the practical dimensions of the green logistics approach and provide a structured basis for understanding logistics system transformation toward sustainability.

The following subsections examine these activities in detail based on established approaches in the literature.

### 3.3.1. Green Transportation

Transportation represents a fundamental component of logistics systems, enabling the movement of goods from production sites to final consumption points. Due to its significant contribution to greenhouse gas emissions, the transport sector has become a central focus of environmental sustainability discussions in logistics (Stojanović et al., 2021). Consequently, developing

environmentally responsible transportation solutions has emerged as a strategic priority within green logistics.

The primary objective of green transportation is to reduce transport-related emissions and minimize the environmental footprint of freight movement. Accordingly, green transport strategies constitute a key operational domain of green logistics systems. Figure 6 illustrates the principal green transportation strategies within this framework.

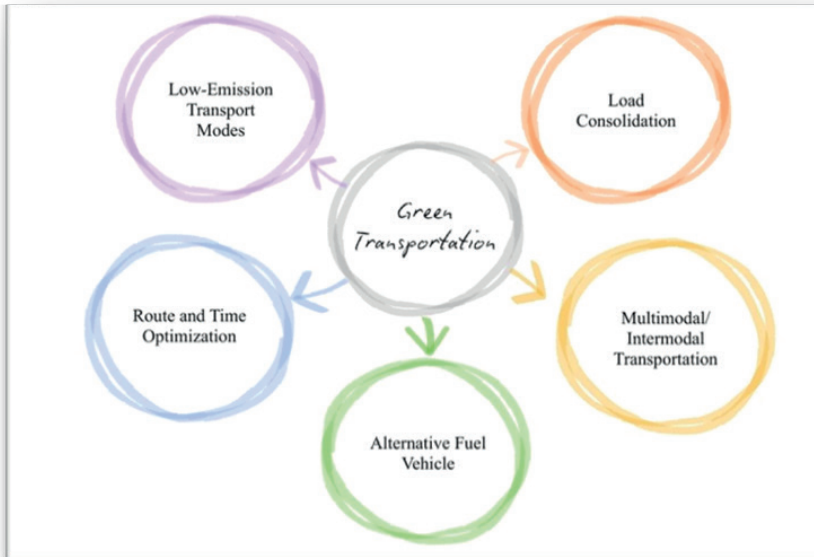


Figure 6 Key Green Transportation Strategies within Green Logistics  
Source: Author's own elaboration based on relevant literature.

Figure 6 presents major green transport applications, including low-emission transport modes, route and time optimization, freight consolidation, alternative fuel vehicles, and multimodal/intermodal transport systems. These complementary strategies collectively represent operational approaches aimed at reducing environmental impacts.

The principal green transportation practices are discussed below.

• Low-Emission Transport Modes

Reducing transport-related emissions is among the most extensively researched topics within green logistics (Olivari et al., 2025). A key strategy involves prioritizing transport modes with superior environmental performance. In selecting transport modes, emission intensity is considered alongside operational criteria such as speed, safety, accessibility, and cost.

Recent studies indicate that integrating drones, renewable energy-powered delivery vehicles, and bicycle-based distribution systems into logistics networks contributes to the diffusion of low-carbon transport solutions.

• *Route and Time Optimization*

Timely and efficient delivery remains a core performance indicator in logistics systems. While traditionally focused on cost and speed, route and scheduling optimization approaches are increasingly being redefined to incorporate environmental criteria. Contemporary models integrate carbon emission and energy consumption metrics alongside conventional operational efficiency indicators (Liu et al., 2025).

Route planning aims to determine transport paths that minimize environmental impacts under constraints such as distance, traffic density, road conditions, and load capacity. Time optimization focuses on reducing delivery windows, travel durations, and idle periods to improve operational efficiency while lowering emissions. Together, these mechanisms contribute significantly to enhancing the environmental performance of transportation systems within the green logistics framework.

• *Freight Consolidation*

Freight consolidation is a fundamental operational tool within green transport logistics. By increasing load factors and reducing the number of trips required, consolidation strategies decrease fuel consumption and greenhouse gas emissions. Reduced trip frequency also contributes to lower traffic congestion, noise pollution, and urban air pollution. Consequently, freight consolidation operationalizes green transport objectives at the practical level (Gupta & Gupta, 2026).

• *Alternative Fuel Vehicles*

Alternative fuel vehicles—including hybrid, electric, hydrogen-powered, and CNG/LNG-powered vehicles—represent central instruments for reducing transport-related emissions. These technologies enable low- or zero-emission freight movement and contribute to improved energy efficiency, thereby potentially reducing long-term operating costs. By decreasing reliance on fossil fuels, alternative fuel technologies support structural transformation aligned with environmental sustainability objectives (Ghorbanali Zadegan & Guo, 2026).

• *Multimodal and Intermodal Transportation*

Multimodal and intermodal transport systems play a crucial role in reducing dependence on road freight and integrating lower-emission transport modes into logistics networks. By combining different transport modes, these systems enhance environmental performance and reduce overall emission

intensity. The literature identifies multimodal and intermodal transport as structural solutions for mitigating transport-related greenhouse gas emissions (Çapar et al., 2025).

- *Fleet Management*

Sustainable fleet management involves the strategic planning, monitoring, and optimization of vehicle fleets to reduce fuel consumption and emissions. It encompasses decisions related to vehicle selection, maintenance practices, operational performance monitoring, and integration with route and scheduling systems. Environmentally efficient vehicle fleets supported by coordinated management and regular maintenance play a decisive role in achieving green transport objectives (Islam et al., 2021).

These practices represent key strategies for reducing the environmental impacts of transportation within green logistics systems. However, the green logistics paradigm extends beyond transportation activities and requires a broader systemic transformation. Accordingly, the following subsection examines sustainable warehousing and logistics facility practices within the framework of green logistics.

### 3.3.2. Green Warehousing and Logistics Facility Operations

Although warehousing was traditionally regarded as a secondary function within logistics systems, it is now recognized as a critical component comparable to transportation activities (Abdul Rahman et al., 2023). Warehouses ensure supply chain continuity and efficiency by enabling the systematic handling, storage, and dispatch of raw materials, semi-finished goods, and finished products (Biçer et al., 2025). Planning parameters such as dwell time, inventory levels, layout configuration, and handling processes directly influence overall logistics performance.

Disruptions in warehousing operations may generate significant supply chain interruptions and operational inefficiencies. As the strategic importance of warehouses has increased, their environmental impacts—particularly energy consumption, emissions, and resource utilization—have received growing attention in the literature (Visse et al., 2026). This development highlights the need to systematically integrate environmental considerations into warehouse planning and operational processes.

Green warehousing differs from conventional warehouse management by embedding environmental sustainability into planning and operational decision-making. It represents a sustainability-oriented management approach based on energy efficiency, renewable energy use, waste reduction, environmentally responsible facility design, and digital system integration. The principal green warehousing practices are illustrated in Figure 7.



Figure 7 Green Warehousing and Logistics Facility Practices  
 Source: Author's own elaboration based on relevant literature.

Figure 7 presents the core components of green warehousing, including energy-efficient design, renewable energy integration, optimization of heating, cooling, and lighting systems, and smart warehouse management technologies. These applications aim to improve

operational efficiency while reducing environmental impacts associated with warehousing and facility operations. The following subsections examine these application areas in detail.

#### • Energy-Efficient Warehouses

Energy-efficient warehouses constitute one of the foundational elements of green warehousing. This approach seeks to reduce energy consumption during storage operations and, consequently, minimize associated environmental impacts. Energy-focused warehouse design and operational practices not only reduce operating costs but also contribute significantly to lowering greenhouse gas emissions (Cannava & Perotti, 2025).

#### • Smart Warehouse Management Systems

Smart warehouse management systems utilize digital monitoring, automation, and decision-support technologies to optimize warehouse processes in line with efficiency and sustainability objectives. By improving inventory management, monitoring energy consumption, and enhancing equipment performance, such systems enable more effective operational

control. The adoption of automation technologies reduces unnecessary internal movements and repetitive handling activities, thereby improving time, energy, and resource efficiency while lowering emissions from warehousing operations (Clavero et al., 2026; Zhang et al., 2026).

• *Optimization of Heating, Cooling, and Lighting Systems*

The strategic planning and management of heating, cooling, and lighting systems—considering energy efficiency, operational intensity, and environmental conditions—constitute a critical component of green warehousing. Optimizing these systems significantly reduces energy consumption and associated greenhouse gas emissions within storage facilities (Jin et al., 2026).

• *Use of Renewable Energy*

The integration of renewable energy sources represents a key component of environmental sustainability within logistics systems. In green warehousing practices, increasing the use of renewable energy is recognized as an effective strategy for reducing greenhouse gas emissions associated with storage activities (Wahyudi et al., 2024). Self-generating warehouses are becoming increasingly common, as facilities capable of producing their own energy enhance both operational efficiency and environmental performance. Renewable energy integration involves meeting facility energy demand through sources such as solar, wind, and geothermal power instead of fossil fuels.

Together with energy-efficient warehouse design, smart management systems, and optimized heating, cooling, and lighting operations, renewable energy adoption demonstrates how warehousing facilities can be aligned with environmental sustainability principles. Addressing storage processes through energy and resource efficiency is therefore essential for improving the environmental performance of logistics systems.

However, the green logistics paradigm extends beyond warehousing operations to include packaging systems used in product transportation and protection. Accordingly, the following subsection examines sustainable packaging practices within the framework of green logistics.

### **3.3.3. Green Packaging**

Packaging is widely recognized as one of the logistics activities with significant environmental impacts (González Romero et al., 2024). Systems used for the protection, transportation, and storage of goods generate considerable pressures through material consumption, energy use, and waste generation. Consequently, reducing the environmental footprint of packaging processes plays an important role in climate change mitigation and resource efficiency improvement.

The green packaging approach emphasizes reducing material use, prioritizing recyclable and reusable solutions, and adopting energy-efficient design strategies. These practices contribute to sustainable logistics systems by lowering packaging-related waste and associated environmental impacts. Figure 8 illustrates the main application areas of the green packaging approach.

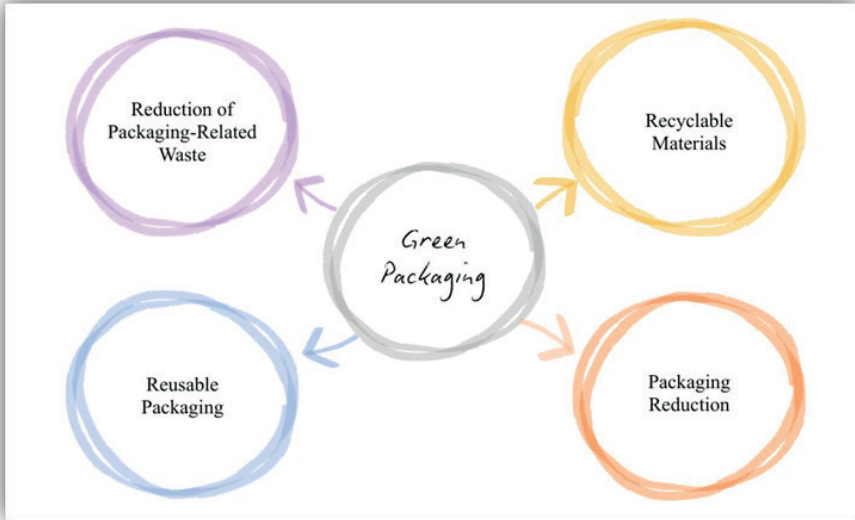


Figure 8 Core Applications within the Green Packaging Framework

Source: Author's own elaboration based on relevant literature.

Figure 8 categorizes green packaging practices into four principal components: reduction of packaging-related waste, use of recyclable materials, development of reusable packaging systems, and strategies for minimizing packaging volume and weight. These components are discussed in the following subsections to further examine the environmental implications of green packaging.

#### • Packaging Reduction

Packaging reduction represents a central strategy within the green packaging framework (Ilhan et al., 2026). This approach seeks to decrease the quantity, weight, and volume of packaging materials without compromising product protection. By reducing packaging inputs, this strategy lowers waste generation and enhances transportation and storage efficiency. As a result, packaging reduction contributes to both environmental performance improvement and operational optimization, positioning it as a strategic tool within sustainable logistics systems.

- *Recyclable Materials*

Recyclable packaging materials are collected after use and reintroduced into production systems through recycling processes. This practice significantly reduces raw material consumption, energy use, and waste generation (Scrioșteanu & Criveanu, 2023). The adoption of recyclable materials thus constitutes a fundamental component of sustainable packaging strategies aimed at mitigating the environmental impacts of logistics activities.

- *Reusable Packaging*

Reusable packaging systems are designed for multiple usage cycles within logistics operations and actively support product transportation and storage processes. Rather than becoming waste after a single use, these packaging units are reintegrated into logistics systems, reducing dependence on single-use packaging. Reusable solutions are therefore regarded as effective instruments for minimizing waste and improving resource efficiency within green packaging practices (González Romero et al., 2024).

Together with packaging reduction and recyclable materials, reusable packaging highlights the critical role of green packaging in lowering the environmental impacts of logistics activities. Aligning packaging processes with sustainability principles represents an important indicator of green logistics systems, particularly in terms of waste reduction and efficient resource utilization.

However, the effective implementation of green logistics also depends on enabling mechanisms that support the monitoring, management, and optimization of operational processes. Accordingly, the following subsection examines digitalization and supporting green logistics mechanisms.

### **3.3.4. Digitalization and Supporting Green Logistics Mechanisms**

Digitalization functions as a key enabler of green logistics by improving the efficiency, transparency, and measurability of logistics operations (Arthur et al., 2026). Through real-time data collection and analytics, digital technologies support resource optimization, emission monitoring, and environmentally informed decision-making.

Technologies such as IoT-based monitoring systems, decision support tools, demand and inventory optimization models, and paperless logistics processes reduce operational inefficiencies while enhancing sustainability performance. Rather than serving merely as supportive tools, digital systems operate as transformative mechanisms enabling the systematic integration of environmental objectives into logistics management. The multidimensional relationship between digitalization and green logistics is illustrated in Figure 9, developed based on insights from the literature.

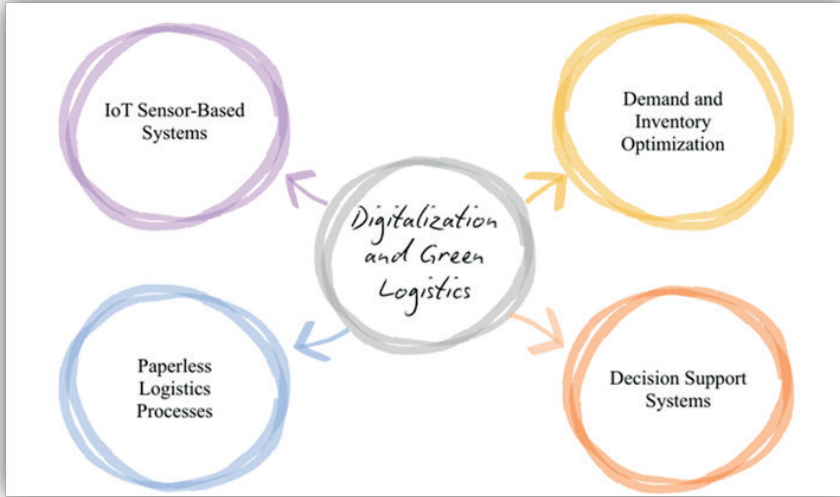


Figure 9 Digitalization and Supporting Mechanisms in Green Logistics

Source: Author's own elaboration based on relevant literature.

Figure 9 presents the principal digital enablers of green logistics, including IoT-based sensor systems, demand and inventory optimization, decision support systems, and paperless logistics processes. These components are discussed in the following subsections to clarify how digitalization contributes to green logistics implementation.

#### • *IoT and Sensor-Based Systems*

Internet of Things (IoT) technologies and sensor-based systems enable the real-time monitoring of the location, status, and environmental conditions of physical assets within logistics operations. Through continuous data streams, parameters such as energy consumption, temperature, humidity, fuel usage, load capacity utilization, and equipment performance can be tracked dynamically. This capability enhances operational efficiency and contributes to minimizing environmental impacts.

The literature indicates that IoT and sensor-based technologies play a significant role in reducing energy and fuel consumption, monitoring and controlling greenhouse gas emissions, improving resource efficiency, and quantifying environmental impacts (Wei & Zhang, 2025). By enhancing data transparency and traceability, these systems strengthen the environmental governance capacity of logistics networks.

### • Decision Support Systems

Decision support systems (DSS) constitute critical tools for the planning, monitoring, and continuous improvement of logistics systems. Given the complexity and multi-variable nature of logistics decision-making processes, data-driven and systematic approaches are essential. Within the context of green logistics, decision support systems extend beyond cost and time optimization to incorporate environmental impact reduction and energy efficiency objectives (Chen et al., 2026).

By integrating environmental performance indicators into decision-making frameworks, DSS enable logistics operations to be evaluated against sustainability benchmarks, transforming sustainability targets into measurable and actionable criteria.

### • Demand and Inventory Optimization

Demand and inventory optimization represent digital approaches that align production volumes and stock levels with actual demand conditions. This approach integrates historical data analysis with predictive modeling techniques. Within green logistics, demand and inventory optimization prevent overproduction and excessive stockholding, thereby reducing resource consumption and limiting environmental impacts (Pasupuleti et al., 2024).

Accurate demand forecasting accelerates inventory turnover rates, reducing warehouse space requirements and associated energy consumption. As such, demand and inventory optimization contribute directly to improving both operational efficiency and environmental performance.

### • Paperless Logistics Processes

Paperless logistics processes refer to the creation, transmission, storage, and management of logistics documentation through electronic systems. By digitizing documentation and record-keeping functions, paper-based resource consumption is significantly reduced, making paperless systems a direct resource-saving mechanism within the green logistics framework (UNCTAD, 2021).

The widespread adoption of digital document management systems decreases the energy consumption, water use, and waste generation associated with paper production, printing, and physical archiving. More broadly, digitalization enhances the traceability, measurability, and manageability of logistics operations, thereby supporting environmentally informed decision-making processes.

However, the effectiveness of green logistics practices depends on the systematic measurement and monitoring of environmental impacts. Accordingly, the following subsection examines carbon footprint management

and environmental performance monitoring within the logistics sector.

### 3.3.5. Carbon Footprint Management and Monitoring Activities

Carbon footprint management and monitoring represent core environmental approaches within green logistics, aiming to measure, track, and reduce greenhouse gas emissions generated by logistics processes (Chhabra et al., 2022). These practices enable the quantification of environmental impacts, identification of primary emission sources, and determination of priority intervention areas.

Regular monitoring allows the environmental performance of logistics operations to be evaluated over time and supports the data-driven development of sustainable logistics strategies. In this respect, carbon footprint management functions not only as a reporting tool but also as an integrated management mechanism that enhances energy efficiency, identifies operational improvement opportunities, and contributes to climate change mitigation efforts.

This process extends beyond emission measurement and requires the cyclical implementation of monitoring, reporting, and reduction strategies. As illustrated in Figure 10, carbon footprint management operates as a systematic and integrated framework developed based on current literature and conceptual approaches.

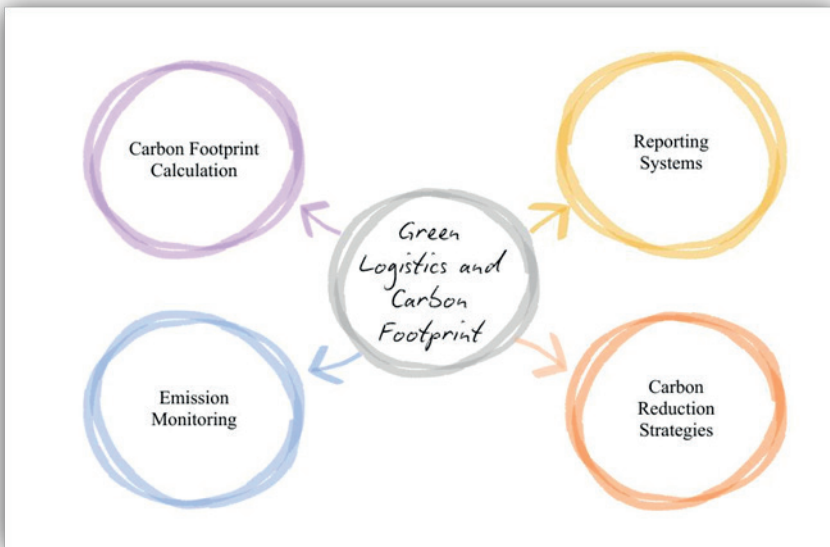


Figure 10 Carbon Footprint Management and Monitoring Framework in Green Logistics

Source: Author's own elaboration based on relevant literature.

Figure 10 presents the core components of carbon footprint management within green logistics in a holistic and cyclical structure. The framework integrates carbon footprint calculation, emission monitoring, reporting systems, and carbon reduction strategies, demonstrating that carbon management is not solely measurement-oriented but requires coordinated implementation of monitoring, reporting, and reduction actions. The main components are outlined below.

• *Carbon Footprint Calculation*

Carbon footprint calculation represents the initial stage of carbon management and monitoring activities. This process involves the quantitative assessment and classification of greenhouse gas emissions generated by logistics operations. In the literature, carbon footprint calculation is defined as an analytical and methodological tool that renders the environmental impacts of logistics activities measurable (Čuček et al., 2012; Perotti et al., 2022).

Given the high energy intensity and fossil fuel dependency of logistics systems, carbon accounting enables the identification of emission sources across specific activities, operational stages, and intensity levels. This facilitates the development of targeted mitigation strategies. Thus, carbon footprint calculation functions not only as a reporting mechanism but also as a decision-support tool guiding the planning of green logistics initiatives.

• *Emission Monitoring*

Emission monitoring constitutes the control and continuity dimension of carbon footprint management (Energy Sustainability Directory, n.d.). It plays a critical role in managing emissions originating from transportation, warehousing, energy consumption, and distribution activities. Through systematic monitoring, emissions can be identified in terms of their activity source, intensity, and temporal distribution.

This structured monitoring process enhances environmental performance management within logistics systems. Identifying high-emission activities, prioritizing operational improvement areas, and tracking progress toward predefined carbon reduction targets are key outcomes that strengthen sustainable logistics governance.

• *Reporting Systems*

Reporting systems serve as environmental information frameworks that collect, analyze, and present greenhouse gas emission data in standardized formats over defined time intervals. By integrating emission data into decision-making processes, these systems support the alignment of logistics

operations with environmental sustainability objectives.

Transparent and structured reporting mechanisms also contribute to regulatory compliance, stakeholder accountability, and corporate sustainability communication.

#### • *Carbon Reduction Strategies*

Carbon reduction strategies comprise practical measures aimed at reducing greenhouse gas emissions across logistics activities. These strategies focus on improving energy efficiency, optimizing operational processes, and minimizing emission sources in transportation, warehousing, and packaging operations, thereby translating green logistics objectives into implementable practices. Existing studies indicate that carbon reduction measures not only mitigate environmental impacts but also enhance operational efficiency (Kamacı, 2025).

Advancements in digitalization and smart technologies have significantly improved the monitoring and effectiveness of emission reduction initiatives. Digital monitoring systems and emission reporting tools enable real-time tracking of emissions, evaluation of operational performance, and comparative assessment of pre- and post-implementation outcomes, transforming carbon reduction efforts into dynamic and continuously improving management processes.

Through the integration of carbon calculation, monitoring, reporting, and reduction mechanisms, carbon footprint management functions as an adaptive governance framework within green logistics systems. While operational practices such as transportation, warehousing, packaging, and digitalization contribute to environmental performance improvements, achieving long-term sustainability requires strategic spatial decisions. Accordingly, the location of logistics facilities and centers emerges as a critical domain representing the spatial dimension of the green logistics approach.

#### **3.3.6. Site Selection**

The selection of locations for logistics centers and warehouses forms a fundamental structural component of logistics operations (Malandri et al., 2026). Spatial decisions directly influence the planning, management, and overall performance of logistics systems and represent one of the most significant long-term strategic considerations within logistics planning (Şahin & Cebi, 2025).

A review of the literature indicates that logistics centers and logistics warehouses are sometimes used interchangeably. Although these facilities share certain location criteria, they differ substantially in functional scope and managerial structure (Du & Bergqvist, 2010). Recognizing these distinctions

is particularly important when environmental sustainability principles are incorporated into location decisions.

• *Logistics Center Site Selection*

Logistics center site selection involves planning integrated logistics zones where multiple logistics activities are coordinated within a unified operational structure. Rather than functioning merely as storage facilities, logistics centers are multifunctional systems in which transportation, storage, distribution, and value-added services are performed simultaneously, serving as strategic nodes within regional and national logistics networks.

Key site selection criteria include multimodal transport connectivity, availability of large land areas, robust infrastructure systems, and alignment with regional development objectives. These factors support balanced and cost-efficient supply chain flows while enabling effective environmental management across logistics networks. Consequently, location decisions extend beyond economic optimization to include environmental performance considerations.

Within the green logistics framework, environmental criteria are increasingly incorporated into traditional location models, aiming to minimize carbon emissions and promote environmentally responsible logistics operations. Renewable energy integration, sustainable infrastructure solutions, and reduced resource consumption have therefore become important components of contemporary site selection processes (Yerlikaya et al., 2023). Recent studies further highlight the growing inclusion of environmental indicators in logistics center location modeling (Chen et al., 2025).

• *Warehouse Site Selection*

The efficient and sustainable execution of storage and distribution activities is fundamental to logistics system performance, making warehouse site selection a strategic planning process. Warehouses function as facilities for temporary storage, intensive handling, and dispatch operations, and traditional location models have primarily emphasized proximity to transport infrastructure, accessibility to demand points, and land-use characteristics. Accordingly, much of the literature has focused on minimizing transport distances, reducing delivery times, and lowering operational costs (Liu et al., 2024).

With the growing emphasis on environmental sustainability, green logistics principles are increasingly incorporated into warehouse location decisions. Criteria such as energy efficiency, carbon footprint reduction, and environmental impact mitigation have become integral components of contemporary site selection models (Baglio et al., 2025). Consequently, warehouse location decisions are now understood not only as instruments of

operational efficiency but also as mechanisms for enhancing environmental performance.

Although logistics centers and warehouses are often used interchangeably in site selection studies, they differ significantly in functional scope, spatial scale, and governance structures. Table 1 provides a comparative framework illustrating these distinctions within both conventional and green logistics perspectives.

*Table 1 Comparative Framework of Logistics Warehouses and Logistics Centers within Conventional and Green Logistics Perspectives*

Comparison Criteria	Logistics Warehouse	Logistics Center	Green Logistics Warehouse	Green Logistics Center
<b>Primary Objective</b>	Storage and preparation for distribution	Integrated execution of logistics activities	Sustainable storage with minimized environmental impacts	Sustainable, integrated, low-carbon logistics network management
<b>Functional Scope</b>	Storage and handling	Storage, transshipment, distribution, value-added services	Energy-efficient storage and green operations	Green transport, storage, distribution, and coordination
<b>Operational Scale</b>	Micro (firm-level)	Macro/regional scale	Micro scale with environmental focus	Macro scale with environmental and regional focus
<b>Transport Integration</b>	Limited transport modes	Multimodal integration	Low-emission and alternative fuel connectivity	Multimodal and low-carbon transport systems
<b>Energy Use</b>	Predominantly fossil-based	Predominantly fossil-based	Renewable energy and energy efficiency	Renewable energy with smart energy management
<b>Carbon Footprint Approach</b>	Limited or no monitoring	Limited operational monitoring	Carbon monitoring and reduction-oriented	Systematic carbon footprint management and reduction strategies
<b>Environmental Management</b>	Limited operational measures	Partial environmental integration	Green building, energy, and waste management	Regional environmental governance and emission optimization
<b>Land and Spatial Planning</b>	Proximity to demand points	Strategic logistics corridors and nodes	Environmentally optimized site selection	Regional planning and sustainable land use
<b>User Profile</b>	Single firm (limited users)	Multiple logistics actors	Firms implementing green logistics	Public-private and multi-stakeholder structure
<b>Strategic Role</b>	Operational efficiency	Supply chain integration	Environmental performance enhancement	Sustainable logistics network governance and regional development

*Source: Compiled and developed by the author based on relevant literature.*

Ultimately, facility location decisions represent a critical spatial dimension of green logistics systems, influencing operational performance, environmental sustainability, and long-term system resilience. Within this paradigm, site selection extends beyond transport efficiency to encompass carbon footprint mitigation, sustainable land-use planning, and integrated environmental management. However, the overall effectiveness of green logistics depends not only on facility location but also on upstream supply chain practices, which are examined in the following section through green procurement and sustainable sourcing approaches.

### **2.3.7. Green Procurement and Purchasing Activities**

Green procurement and purchasing activities represent a fundamental component of sustainable supply chain management and green logistics governance (Teixeira et al., 2018). By integrating environmental considerations into sourcing decisions, these practices directly influence the environmental performance of logistics systems from the earliest stages of the supply chain.

Procurement decisions significantly affect the carbon footprint, energy consumption, and waste generation associated with logistics operations. Approaches that overlook environmental criteria may increase emissions and resource inefficiencies; therefore, green procurement is widely recognized as a strategic dimension of green logistics rather than merely an operational practice.

#### *• Environmentally Friendly Supplier Selection*

Environmentally responsible supplier selection offers significant advantages in the context of sustainable supply chain management and green logistics implementation. Prioritizing suppliers that adopt low-emission production methods and energy-efficient technologies contributes to reducing the overall carbon footprint of the supply chain. This, in turn, directly supports organizations in achieving their environmental sustainability objectives.

#### *• Local Sourcing*

Local sourcing practices are considered an environmentally responsible approach within green logistics frameworks. In addition to environmental benefits, they also generate economic value by supporting local production and employment. Preference for local suppliers shortens delivery times, enhances responsiveness to potential disruptions, and reduces transport-related carbon emissions due to decreased supply distances. In this respect, local sourcing emerges as a strategic practice that supports both environmental and operational sustainability (Ali et al., 2023).

• *Preference for Low-Carbon Products*

The preference for low-carbon products represents one of the fundamental components of green procurement and purchasing activities and plays a strategic role in achieving sustainability objectives within the logistics sector. Selecting products that generate lower greenhouse gas emissions throughout their life cycle contributes to reducing environmental impacts across the supply chain. Lower energy requirements in transportation and storage processes further enable the reduction of indirect emissions. Such preferences enhance corporate sustainability performance and positively influence brand reputation. In this sense, low-carbon product selection constitutes an integrated approach that delivers both environmental and competitive advantages in logistics operations (C. Cheng et al., 2022).

• *Supplier Environmental Performance Criteria*

Supplier environmental performance criteria constitute essential benchmarks within green procurement practices, enabling the systematic evaluation of suppliers based on indicators such as energy efficiency, waste management, emission levels, resource-use efficiency, and environmental management systems (Tuzkaya et al., 2009). Incorporating these criteria into supplier selection processes ensures that purchasing decisions are guided not only by cost and quality considerations but also by environmental responsibility.

Since suppliers represent a significant share of the indirect carbon footprint of logistics activities, environmentally oriented evaluation mechanisms play a critical role in promoting green logistics practices across the supply chain and supporting emission reduction at the source.

Overall, the themes discussed in this section frame green logistics as a multidimensional system supported by both operational practices and strategic decision-making processes. Beyond improving sectoral environmental performance, green logistics contributes to broader sustainability objectives, including resource efficiency, climate change mitigation, and sustainable production and consumption patterns. In this sense, green logistics represents the logistics-specific implementation of an integrated sustainability approach encompassing economic, environmental, and social dimensions.

**Conclusion**

This chapter has examined the environmental impacts of the logistics sector and the responses developed within the framework of green logistics. Growing climate pressures, accelerating resource depletion, and increasing environmental degradation necessitate a structural reassessment of the traditional speed- and cost-oriented logistics paradigm. In this context, green logistics emerges as a long-term transformation approach aimed at reducing

the environmental footprint of logistics systems.

The analysis demonstrates that the environmental impacts of logistics are multilayered and interconnected, affecting both global climate systems and local ecosystems. Accordingly, green logistics has been conceptualized as an integrated framework encompassing transportation, warehousing, packaging, digitalization, carbon footprint management, and site selection. Rather than representing isolated environmental practices, these components collectively redefine logistics management within ecological constraints.

Positioned as a strategic governance approach, green logistics enhances resource efficiency, reduces emission intensity, and improves system-wide environmental performance. By embedding sustainability considerations into operational processes and strategic decision-making, the chapter provides a conceptual foundation for understanding how logistics systems can be restructured within planetary boundaries and evolving sustainability requirements.

Building upon this foundation, the subsequent chapter examines green logistics within the broader framework of sustainable development, analyzing its alignment with the United Nations Sustainable Development Goals (SDGs) and comparatively evaluating global policy models and implementation practices across different regions.

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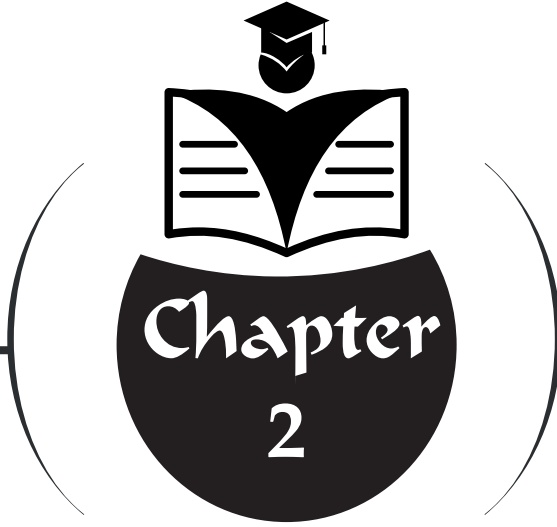
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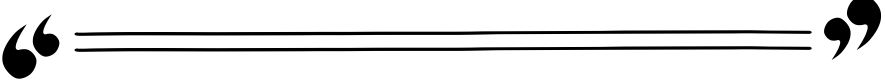
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**GREEN LOGISTICS IN THE CONTEXT OF  
SUSTAINABLE DEVELOPMENT: GLOBAL  
POLICIES AND PRACTICES**



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## Introduction

Sustainable development represents a holistic development paradigm that seeks to achieve a simultaneous balance among economic growth, social welfare, and environmental protection. In the twenty-first century, the escalating climate crisis, the depletion of natural resources, and the expansion of global supply chains have necessitated a reconsideration of this paradigm, particularly within the logistics sector. Due to their multi-layered structure encompassing transportation, warehousing, packaging, distribution, and reverse logistics processes, logistics activities exert significant influence on energy consumption, greenhouse gas emissions, and land use patterns. This situation positions the logistics sector at the center of sustainable development debates. Nevertheless, the rapid expansion of global logistics networks has often outpaced the implementation capacity of sustainability policies, transforming the redesign of logistics systems within the framework of sustainable development from a strategic preference into a structural necessity.

In recent years, the concept of green logistics has increasingly been addressed in the literature not merely as a technical approach aimed at reducing environmental impacts, but as a strategic transformation framework integrated with sustainable development goals (Ahmad et al., 2025; Tetteh et al., 2024). This approach envisages the restructuring of logistics systems through the reduction of carbon emissions, enhancement of energy efficiency, widespread adoption of circular economy practices, and integration of digital technologies. However, existing studies largely examine the relationship between green logistics and sustainable development goals through specific indicators or sectoral performance metrics, while comprehensive comparative analyses addressing global policy models and implementation mechanisms remain limited.

Within this context, this chapter aims to provide a systematic conceptual and policy-oriented assessment by positioning green logistics practices within the framework of the United Nations Sustainable Development Goals. The primary contribution of the chapter lies in examining the relationship between green logistics and sustainable development not only from an environmental perspective, but also through the interconnected dimensions of energy transition, innovation, governance, and economic competitiveness. Furthermore, through a comparative examination of regional policy approaches, the chapter explores how the transformation toward green logistics is shaped within different institutional and regulatory contexts.

Accordingly, the chapter is structured into two main sections. The first section analytically examines the relationship between green logistics and sustainable development within the framework of the Sustainable Development Goals. The second section comparatively evaluates global policy

and implementation models of green logistics practices through selected examples from the European Union, Asian countries, the Americas, and Oceania.

### **1. The Relationship Between Green Logistics and Sustainable Development**

The 2030 Agenda for Sustainable Development, adopted in 2015 by all United Nations member states, consists of 17 Sustainable Development Goals (SDGs) and 169 associated targets (United Nations, 2015). This framework aims to achieve economic growth, social inclusion, and environmental protection simultaneously. Considering the increasing complexity of global production and consumption systems and the spatial expansion of supply chains, the logistics sector occupies a central position in sustainable development debates. Within this context, green logistics interacts with the environmental, economic, and social dimensions of sustainable development in a multilayered manner. The literature indicates that environmental and economic dimensions have received particular emphasis (Kwilinski et al., 2023; Matantseva et al., 2021; Zaman & Shamsuddin, 2017).

From an environmental perspective, the carbon footprint of the logistics sector is evaluated through direct emissions resulting from fuel consumption, indirect emissions associated with purchased energy, and broader indirect emissions generated throughout supply chain processes.

From an economic standpoint, although green logistics practices may require substantial initial investments, they provide long-term advantages such as improved operational efficiency, energy savings, and avoidance of carbon-related taxes (Andruetto et al., 2025). Policy instruments such as the European Union's Carbon Border Adjustment Mechanism increasingly compel firms to restructure their logistics operations. Consequently, green logistics has evolved from being merely an environmental preference into a strategic factor of competitive advantage.

From a social perspective, low-emission and low-noise logistics systems contribute to improved urban quality of life and are reported to have positive effects on occupational health and safety (Matusiewicz, 2019; Ren et al., 2019). Particularly in densely populated urban centers, the widespread adoption of sustainable distribution systems contributes to reducing health risks associated with air pollution and noise exposure (). In this regard, green logistics should be understood not only as a pathway toward environmental sustainability but also as a comprehensive transformation domain that supports social welfare and quality of life.

Within this framework, green logistics practices intersect directly with multiple Sustainable Development Goals through mechanisms such as the

use of renewable energy, improvements in energy efficiency, reduction of greenhouse gas emissions, circular economy practices, environmentally friendly infrastructure, and digitalization. This demonstrates that the logistics sector functions not merely as a supporting mechanism but also as an active implementing actor in the pursuit of sustainable development.

### **1.1. Green Logistics and the Sustainable Development Goals**

In order to systematically examine the relationship between green logistics practices and sustainable development, this section adopts the United Nations Sustainable Development Goals (SDGs) framework as an analytical reference point. The SDGs present a holistic development approach that addresses economic growth, social inclusion, and environmental protection not as independent dimensions but as mutually interacting components. This integrated structure enables logistics activities to be evaluated not only in terms of economic outputs but also through their environmental impacts, energy use, resource efficiency, and broader implications for social welfare.

The logistics sector constitutes the backbone of global production and consumption systems, functioning as a critical infrastructure that ensures the continuity of flows of goods and services. However, the increasing volume of global trade, the expansion of e-commerce activities, and the growing spatial complexity of supply chains have enlarged the environmental footprint of logistics operations, placing the sector at the center of sustainability debates. Consequently, green logistics should be understood not merely as an operational improvement approach but as a transformation domain directly linked to the global development agenda.

A review of the literature indicates that the relationship between green logistics and the SDGs is generally structured around three principal axes:

- Environmental protection and ecosystem sustainability
- Energy transition and climate action
- Economic growth, innovation, and governance

The environmental protection axis encompasses the reduction of greenhouse gas emissions, prevention of air pollution, optimization of natural resource use, and waste management practices. The energy transition and climate action axis focuses on transformation mechanisms such as renewable energy adoption, energy efficiency improvements, low-carbon transportation systems, and alternative fuel technologies. The economic growth, innovation, and governance axis is associated with sustainable infrastructure investments, digital logistics systems, supply chain transparency, and corporate sustainability policies.

Within this analytical framework, the contribution of green logistics practices to sustainable development goals is evaluated not only in terms of

direct alignment with individual goals but also through interactions among multiple goals. For example, energy-efficient transportation systems contribute simultaneously to climate action while also supporting sustainable cities and responsible production and consumption patterns. This demonstrates that green logistics functions as a strategic instrument capable of creating linkages among the Sustainable Development Goals. This multidimensional relationship network is visually illustrated in Figure 1, where the goals that directly interact with logistics activities are highlighted through color coding.



Figure 1 Sustainable Development Goals

Source: Adapted by the author from United Nations Sustainable Development Goals website.

Below, selected Sustainable Development Goals that are directly or indirectly associated with green logistics are discussed in detail within the context of logistics activities and their respective contribution mechanisms.

### • SDG 6 – Clean Water and Sanitation

Reverse logistics practices and green logistics activities enable the systematic collection and recovery of waste, thereby reducing the pressure of logistics-related pollutants on water resources. Liquid wastes, chemical leakages, and packaging-related residues generated during port operations, warehousing activities, and industrial transportation pose significant risks to both surface and groundwater systems. Through waste management practices, environmental risk assessment, and green port initiatives, these risks can be minimized, contributing to the protection of water quality. The literature emphasizes the direct relationship between sustainable port management, environmentally friendly logistics practices, and SDG 6 (Anandhabalaji, 2025; İnal & Dere, 2024; Scown et al., 2011).

### • **SDG 7 – Affordable and Clean Energy**

Green transportation applications such as electric vehicles, hydrogen-powered transport systems, and biofuel-based logistics solutions reduce dependence on fossil fuels and promote the adoption of clean energy. In addition, warehouses equipped with solar panels, energy-efficient lighting systems, and smart energy management infrastructures contribute to lowering the carbon intensity of logistics centers. Logistics systems based on renewable energy sources support energy transition by reducing sectoral carbon intensity (Y. Chen, 2025; Yu et al., 2026).

### • **SDG 8 – Decent Work and Economic Growth**

Green logistics investments—including digital logistics solutions, environmental technologies, and sustainable logistics infrastructure projects—are creating new employment opportunities while supporting green economic growth. In this way, a balance between economic development and environmental protection, both core objectives of sustainable development, can be achieved (Barakat & Gerged, 2025; Fritz et al., 2025; Khan, 2019).

### • **SDG 9 – Industry, Innovation and Infrastructure**

Automation systems, smart logistics centers and warehouses, artificial intelligence-supported route optimization, and low-carbon logistics operations promote the development of innovative, resilient, and sustainable logistics systems (W. Chen et al., 2024; Gupta et al., 2026).

### • **SDG 11 – Sustainable Cities and Communities**

Low-emission urban logistics activities—including urban distribution systems, micro-distribution centers, bicycle logistics, and electric delivery solutions—play a significant role in improving urban quality of life by reducing air pollution and noise levels in cities (Naganawa et al., 2025; Pan et al., 2021).

### • **SDG 12 – Responsible Consumption and Production**

Reuse systems, environmentally friendly packaging solutions, reverse logistics, low-carbon product selection, and integrated waste management practices enable more efficient and circular use of resources (Sonar et al., 2024).

### • **SDG 13 – Climate Action**

Carbon footprint measurement, emission monitoring and reporting, emission reduction targets, and carbon-neutral logistics strategies enable the logistics sector to take an active role in combating climate change (Ahmad et al., 2025; Tetteh et al., 2026).

### • **SDG 15 – Life on Land**

Sustainable warehouse site selection, ecosystem-sensitive route planning, circular supply chains, reverse logistics applications, carbon footprint

measurement, and digital logistics solutions reduce pressures on terrestrial ecosystems (Güçlü & Senel, 2024; Tetteh et al., 2024). These practices enable logistics infrastructure to be planned in accordance with ecological thresholds and promote the institutional integration of environmental sensitivity into land-use decision-making processes.

### • **SDG 17 – Partnerships for the Goals**

The widespread adoption of green logistics practices is facilitated through collaborations among public institutions, private sector actors, financial organizations, and international institutions. Such partnerships accelerate sustainable logistics transformation through knowledge sharing, technology transfer, and green financing mechanisms (Chauhan et al., 2022; Zalluhoğlu et al., 2025).

Based on the findings emphasized in the literature, the multidimensional relationship between green logistics practices and the Sustainable Development Goals is summarized within a systematic framework. Table 1 presents the SDGs associated with green logistics in the literature and the corresponding contribution mechanisms in an analytically integrated manner.

*Table 1 Contribution Mechanisms of Green Logistics Practices to the SDGs Identified in the Literature*

SDG	Logistics Practice	Contribution Mechanism	Related Axis
SKA 6	Reverse logistics, green port practices	Reduction of water pollution	Environmental protection
SKA 7	Electric vehicles, renewable energy-powered warehouses	Energy transition	Energy & Climate
SKA 8	Green infrastructure investments	Green employment creation	Economic growth
SKA 9	Smart logistics systems	Innovative and resilient infrastructure	Innovation
SKA 11	Micro-distribution centers, low-emission delivery systems	Improvement of urban quality of life	Urban sustainability
SKA 12	Circular packaging systems, reverse logistics	Resource efficiency	Circular economy
SKA 13	Carbon footprint measurement, carbon-neutral logistics strategies	Climate action	Climate policy
SKA 15	Ecosystem-sensitive site selection	Habitat protection	Ecological sustainability
SKA 17	Public–private partnerships	Institutional collaboration	Governance

*Note; The SDG–green logistics linkages presented in this table are structured based on the studies emphasized in the existing literature. The contribution mechanisms are synthesized by the author through a conceptual analysis of the reviewed sources.*

The above evaluation demonstrates that green logistics practices maintain a multidimensional and intersecting relationship with the Sustainable Development Goals. These contributions extend beyond the reduction of environmental impacts and generate structural effects in areas such as energy transition, innovative infrastructure development, economic transformation, ecosystem protection, and institutional collaboration. In this respect, green logistics should be positioned not merely as a technical approach aimed at improving operational efficiency, but as a strategic transformation domain capable of generating synergies among sustainable development objectives.

However, the scope and implementation of these contributions vary according to countries' policy priorities, regulatory frameworks, technological infrastructures, and institutional capacities. Therefore, examining practical applications and policy instruments is essential for understanding how green logistics integrates with sustainable development goals. Accordingly, the following section analyzes how green logistics practices are structured at the global scale and supported through different policy instruments, drawing upon examples from various countries and regions.

## **2. Green Logistics Practices Worldwide**

Today, many countries have incorporated green logistics practices as a core component of their national sustainable development strategies and have developed corresponding policy instruments and implementation models. The green logistics approach is no longer limited to providing a theoretical framework; rather, it is being implemented through concrete policy mechanisms and sector-based applications across different countries.

Within this context, holistic green logistics-oriented strategies are increasingly adopted to reduce the environmental impacts of the logistics sector and to establish systems aligned with sustainable development objectives. This section examines how green logistics practices are integrated with the Sustainable Development Goals through selected country examples representing different regional policy approaches and implementation models.

### **European Union Countries**

The European Union stands out as one of the regions with the most comprehensive and binding policies in the field of green logistics. Under the European Green Deal and the Fit for 55 policy package, the EU aims to reduce greenhouse gas emissions originating from transport and logistics activities by 55% by 2030 and to achieve carbon neutrality by 2050 (European Commission, n.d.).

In line with these objectives, low-emission transportation systems, energy-efficient logistics centers, and circular economy-based reverse logistics models are increasingly being implemented across Europe. The European

Commission's *Transport and the Green Deal* framework specifically promotes the widespread adoption of electric and hydrogen-powered vehicles alongside the expansion of alternative fuel infrastructure (European Commission, 2025).

Within this policy framework, renewable energy-powered green logistics centers, rooftop solar panel installations, smart warehouse automation systems, and building energy management technologies are actively supported across Europe, enabling logistics infrastructure to be restructured in alignment with environmental sustainability principles (Taş & Aylak, 2022).

These policies and practices align with findings in the literature indicating that green logistics transformation progresses more rapidly under binding regulations and multi-actor governance structures. In particular, the strengthened coordination role of logistics service providers (3PL–4PL) has generated measurable impacts on both environmental and economic performance.

### **Asian Countries**

In Asian countries, green logistics practices have largely evolved through urban distribution systems and digitalization-oriented solutions. This development is primarily driven by rapid urbanization and the growing need to provide efficient and sustainable responses to increasing logistics demand.

Within China's 14th Five-Year Plan (2021–2025), the logistics system is targeted to become smarter, greener, and more efficient. The plan encourages the integration of big data, 5G technologies, and artificial intelligence into logistics operations while promoting recyclable packaging systems and energy-efficient transport equipment. It also includes the establishment of national cold-chain logistics centers and the integrated development of distribution systems (The State Council of the People's Republic of China, 2021).

In Japan, the Green Growth Strategy promotes artificial intelligence-based route optimization, autonomous and electric transportation systems, and carbon footprint monitoring platforms. Companies such as Toyota Logistics and Japan Post have implemented concrete initiatives aimed at reducing environmental impacts through smart warehouse management systems and low-emission transport fleets (METI, 2022).

### **The Americas**

Across the American continent—particularly in the United States—green logistics practices have largely expanded through market-based mechanisms, voluntary programs, and private-sector leadership. Global companies such as Amazon, UPS, and FedEx are restructuring distribution processes through green transportation systems in line with their carbon-neutral commitments. These

companies' net-zero emission targets for 2040 are clearly articulated in their official sustainability strategies (Amazon, n.d.; FedEx Corporation, n.d.; UPS, n.d.).

The SmartWay Program, implemented by the U.S. Environmental Protection Agency (EPA), was developed to measure transportation-related emissions, improve fuel efficiency, and support environmental performance reporting among logistics firms (EPA, 2025). The program is widely recognized as one of the most prominent voluntary mechanisms for quantifying environmental performance within the logistics sector.

Additionally, California's Advanced Clean Fleets (ACF) regulation mandates the transition of specific vehicle fleets toward zero-emission systems, aiming to improve air quality and public health (California Air Resources Board, n.d.). The adoption of low-carbon fuels in air cargo transportation has also been increasing (United Cargo, n.d.).

### **Oceania**

In Oceania, particularly in Australia and New Zealand, green logistics practices primarily focus on port management, low-emission transport solutions, smart port initiatives, and clean energy transitions. Renewable energy-based port infrastructure and low-emission transportation systems constitute key implementation areas within the region.

The Australian Government's *Transport and Infrastructure Net Zero Roadmap and Action Plan* outlines a comprehensive transformation strategy aimed at achieving net-zero greenhouse gas emissions from transport and infrastructure systems by 2050. Key policy priorities include transport decarbonization, expansion of renewable energy use, promotion of low-carbon and alternative fuels, and development of electric transport systems (Australian Government, n.d.).

Ports across the region also play a central role in green logistics strategies. Green port concepts and resilient infrastructure plans are being developed to reduce environmental impacts, while energy efficiency, clean energy adoption, and emission reduction targets are implemented across entire logistics chains (Haskoning, 2022).

Selected country examples of green logistics practices worldwide demonstrate that green logistics is implemented through diverse policy instruments and application models across different geographical contexts. Nevertheless, these practices share common objectives, including reducing carbon emissions, improving energy efficiency, and aligning logistics systems with sustainable development goals. The comparative assessment presented in Table 2 clearly illustrates how green logistics practices are translated into concrete policies and operational practices at the global scale and how they relate to the Sustainable Development Goals.

*Table 2 Global Green Logistics Practices and Their Relations with the Sustainable Development Goals*

Country/ Region	Green Logistics Practice	Example	Key Impact	Related SDGs
<b>Netherlands</b>	Green port development and renewable energy integration	Port of Rotterdam (electric cranes, wind energy systems)	Reduction of CO <sub>2</sub> emissions and improvement of energy efficiency	SDG 9, SDG 11, SDG 13, SDG 17
<b>Germany</b>	Carbon-neutral logistics and smart warehouse systems	DHL GoGreen Program	Reduction of carbon footprint and digitalization	SDG 9, SDG 12, SDG 13, SDG 17
<b>Sweden</b>	Fossil-free transportation	Biomethane-powered truck fleets	Reduction of fuel-related emissions	SDG 7, SDG 12, SDG 13
<b>China</b>	Micro-distribution centers and electric delivery systems	Shenzhen electric distribution network	Reduction of urban air and noise pollution	SDG 11, SDG 13, SDG 9
<b>Japan</b>	AI-supported route optimization	Toyota Logistics AI systems	Fuel savings and time efficiency	SDG 9, SDG 12, SDG 13
<b>France</b>	Electric delivery vehicles	La Poste electric vehicle fleet	Reduction of noise and emissions	SDG 11, SDG 13, SDG 7
<b>United States</b>	Renewable energy-powered logistics warehouses	Amazon solar-powered logistics centers	Carbon-neutral infrastructure and energy savings	SDG 7, SDG 9, SDG 12, SDG 13

*Source: Compiled and developed by the author based on relevant literature.*

The examples presented in Table 2 indicate that while green logistics practices are implemented through diverse policy instruments and technological approaches across countries, they converge around shared sustainability objectives such as carbon emission reduction and energy efficiency improvement.

The country and regional cases discussed in this section reveal that green logistics practices are shaped globally around common environmental goals while exhibiting regional differences in implementation tools, regulatory frameworks, and governance mechanisms. Binding regulations and integrated policy packages dominate in the European Union, whereas digitalization and urban logistics solutions play a defining role in Asian countries. In the Americas, market-based and voluntary mechanisms are more prominent, while in Oceania institutional strengthening occurs primarily through port management and infrastructure transformation initiatives.

These variations demonstrate that green logistics does not follow a uniform model but represents a dynamic transformation process shaped by regional economic structures, technological capacities, and policy priorities. Nevertheless, all cases share common objectives: reducing carbon emissions,

improving energy efficiency, and aligning logistics systems with sustainable development goals. This confirms the positioning of green logistics as a strategic instrument for achieving environmental sustainability at the global scale.

### 2.1. Comparative Analysis of Global Green Logistics Policy Models

An examination of different regional and country cases reveals that while green logistics practices converge around common sustainability objectives, they display significant differences in terms of policy instruments, implementation mechanisms, and institutional structures. This variation demonstrates that the green logistics transition is not merely a technical process but also a governance-driven transformation shaped by institutional capacity, regulatory approaches, and market dynamics.

The European Union model is primarily structured around binding regulations and comprehensive supranational policy frameworks. Integrated policy packages such as the *European Green Deal* and *Fit for 55* transform the logistics sector directly by establishing legally binding emission reduction targets. This approach can be characterized as a regulation-based transformation model grounded in multi-actor governance structures. Instruments such as mandatory reporting requirements, carbon pricing mechanisms, and emission standards systematically reshape sectoral behavior.

In the United States, by contrast, green logistics transformation largely progresses through market-based mechanisms and voluntary programs. Initiatives such as the EPA's *SmartWay Program* provide firms with tools for performance measurement and environmental reporting; however, transformation is primarily driven by incentives and competitive advantage rather than binding regulatory obligations. This model may therefore be described as an approach based on corporate initiative and private-sector leadership. While state-level policies—such as California's mandatory zero-emission fleet regulations—introduce stronger regulatory frameworks, a comprehensive nationwide structure comparable to that of the European Union remains absent.

In Asian countries, particularly in the cases of China and Japan, state-supported strategic planning and technology-driven transformation play a dominant role. Through five-year development plans, national strategies, and industrial policies, green logistics development is systematically guided at the national level. Digitalization, artificial intelligence applications, and smart infrastructure investments serve as primary instruments of logistics transformation. This model reflects a hybrid structure combining centralized planning with technology-intensive transformation.

In the Oceania region, decarbonization strategies are primarily

implemented through port infrastructure and transportation system reforms. Net-zero roadmaps, infrastructure modernization programs, and renewable energy integration constitute the main policy instruments. This approach can be characterized as an infrastructure-oriented and sector-specific transformation model.

This comparative analysis demonstrates that the green logistics transition cannot be reduced to a single policy model; rather, it represents a diversified transformation process shaped by varying governance approaches and institutional capacities. Regulation-based models possess the potential to generate faster and more binding outcomes, whereas market-based approaches promote transformation through competition and corporate initiative. State-directed technology strategies, on the other hand, facilitate structural restructuring through digitalization and infrastructure investment.

Accordingly, the success of green logistics transformation depends not solely on technological innovation but also on the consistency of regulatory frameworks, the reliability of monitoring and reporting systems, the effectiveness of financial incentive mechanisms, and the institutional capacity supporting public–private collaboration. These differences suggest that policy design should prioritize context-sensitive and hybrid approaches rather than a uniform model. In this regard, the Sustainable Development Goals provide an analytical reference framework that enables systematic comparison across diverse policy models.

### **Conclusion**

Green logistics, within the framework of sustainable development goals, should be understood not merely as a technical field aimed at reducing environmental impacts, but as a multidimensional transformation process integrating economic competitiveness, innovation capacity, and institutional governance structures. The evaluations presented in this chapter demonstrate that green logistics practices maintain a multilayered and reciprocal interaction with the Sustainable Development Goals. In particular, the environmental dimension (SDGs 6, 7, 12, 13, and 15) provides direct areas of contribution through energy efficiency, emission reduction, and resource conservation, while the economic and innovation dimensions (SDGs 8 and 9) are closely associated with the sector's competitiveness and transformation capacity. These findings indicate that green logistics constitutes not a complementary element but a structural component of sustainable development.

An examination of global practices reveals that the green logistics transition does not follow a uniform model; rather, it evolves under diverse institutional structures, regulatory frameworks, and market mechanisms. Binding regulations and multi-actor governance mechanisms play a decisive role within the European Union, whereas voluntary programs and market-

based instruments are more prominent in the United States. In Asian countries, state-directed and technology-oriented strategies dominate, while infrastructure-based decarbonization policies stand out in the Oceania region. These variations demonstrate that sustainable logistics transformation requires context-sensitive, flexible, and integrated policy designs.

However, the success of this transformation depends not only on policy design but also on the institutionalization of performance measurement systems and the strengthening of data-driven decision-making mechanisms. Carbon accounting, life cycle assessment, and sustainability reporting systems enable green logistics practices to generate measurable and comparable outcomes. Nevertheless, challenges associated with measuring Scope 3 emissions across supply chains, limitations in data transparency, and the growing prevalence of symbolic sustainability practices complicate the evaluation of the transformation's actual impact. This situation highlights the need to strengthen institutional accountability alongside technological advancement.

It is also evident that green logistics practices do not develop uniformly at the global scale. While developed countries benefit from stronger financial resources, advanced digital infrastructure, and higher institutional capacity, developing countries often face investment constraints and limited access to technology, which may slow the transformation process. This disparity indicates that sustainable logistics policies should incorporate not only environmental objectives but also mechanisms aimed at capacity building, technology transfer, and improvements in governance quality.

In conclusion, green logistics represents a strategic transformation domain through which sustainable development goals are operationalized within logistics systems. In the coming period, holistic approaches that simultaneously address policy design, performance measurement, digitalization, and supply chain integration will determine the durability and effectiveness of this transformation. From this perspective, green logistics requires not only the improvement of existing systems but also the structural reconfiguration of global production and consumption networks in alignment with sustainability principles.

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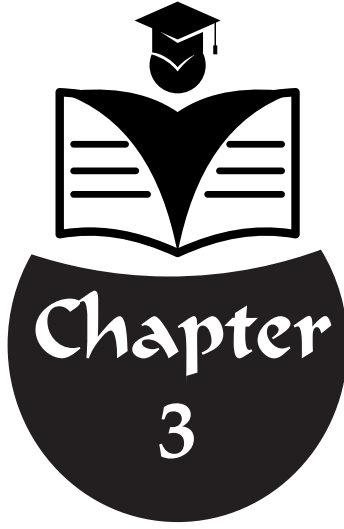
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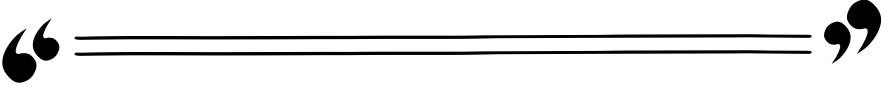
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## **FINANCIAL IMPACTS AND INVESTMENT COSTS OF GREEN LOGISTICS**



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## **1. Introduction: Green Logistics as a Financial Transformation**

Logistics refers to the processes within business that includes the planning, control, and implementation of the flow of goods, information and money between point of origin and the end consumer (Blanco and Sheffi, 2024). These processes are carried out by using an integrated management of transportation, warehousing, inventory, as well as financing across the business and its supply chain. These activities, however, are all considered to be highly energy-intensive and are found to contribute substantially to the pollution in urban areas, increasing noise, accidents, and greenhouse gas emissions (Abbasi and Nilsson, 2016).

With the expansion of global supply chains and the rapid growth of e-commerce, competition in logistics services has intensified, also causing an increase in the environmental footprint of logistics operations. Traditionally, decisions regarding logistics primarily focused on cost minimization, profit maximization, and increasing customer satisfaction. As a result of expansion, with the growing public awareness for the environment and intensifying climate change, logistics has become a critical focal point for climate policy, sustainability regulation, and corporate responsibility frameworks (McKinnon et. al., 2015). Therefore, it is important to note that the focus did not just shift, but it has expanded to include issues such as environmental control, and sustainability. Now, transportation providers are increasingly required to lower greenhouse gas emissions from their fleets to support the development of green transportation, warehouse operations prioritize energy efficiency and waste reduction to establish the energy-efficient warehouses, reverse logistics, and product designs are being modified to enhance recyclability and reuse (Rogers and Tibben-Lembke, 2001).

In response to these pressures, green logistics has emerged as an integrated approach aimed at reducing the environmental impacts of logistics activities while maintaining operational effectiveness. Green logistics specifically seeks to minimize the environmental footprint of logistics activities by reducing carbon emissions, noise, and waste, while simultaneously advancing economic efficiency, social responsibility, and environmental sustainability. In contrast to conventional logistics approaches, green logistics places greater emphasis on environmentally responsible practices that enhance logistics system performance while safeguarding existing infrastructure (Ozekenci and Nur, 2025).

Although initially framed primarily as an environmental or ethical concern, green logistics has increasingly evolved into a financial and strategic issue. The financial sector is among the most important factors that drive economic development. The more efficiently the financial resources are

utilized the more innovative the financial industry becomes, which at that point can then stimulates a growth in economy (Afzal et. al., 2021). Rising energy prices, carbon pricing mechanisms, regulatory compliance costs, and investor scrutiny have transformed environmental performance into a determinant of financial outcomes (Patra, 2018). In other words, cost formation, investment decisions, and risk exposure, are all influenced by environmental requirements, whereas market forces such as energy prices, carbon regulation, and investor expectations directly shape financial outcomes. This transformation necessitates a financial re-interpretation of green logistics. Rather than viewing sustainability initiatives as discretionary costs, firms must assess them as long-term investments with measurable financial implications incorporating long-term value creation, risk management, and capital allocation.

This chapter analyzes green logistics from a financial perspective, focusing on investment costs, payback dynamics, carbon-related instruments, ESG considerations, and financing models. The chapter proceeds by first examining how green logistics reshapes cost structures and financial performance at the firm level, followed by an evaluation of the investment costs and appraisal of green logistics initiatives, the role of carbon pricing and public incentives in financial decision-making, the interaction between ESG performance and the cost of capital, and finally the financial models that support the implementation of green logistics investments.

## **2. Financial Perspective: How Does Green Logistics Change Firm Economics?**

Analyzing the financial implications of green logistics requires examining how environmental initiatives affect and change the structure of logistics operations economically. These initiatives will cause a change in how costs are incurred, as well as how risks are managed, and value is created over time. For this reason, this part of the chapter lays the groundwork to assess green logistics investments by examining their cost structures, financial performance implications, and the resulting transition from trying to keep costs to a minimum to basically create value.

### **2.1. Cost Components of Green Logistics**

Logistics industry is said to be more energy-intensive when compared to many other industries. It, therefore, becomes inevitable to experience adverse environmental outcomes from logistics activities, most notable being high amounts of greenhouse gas emissions (Laari et al., 2018; Zhang et al., 2020). Due to their central role in managing physical infrastructure and coordinating complex operational networks, logistics firms hold a key role in determining the environmental footprint of supply chains. For this reason, combining their critical role and the adverse effects of the activities

they undergo, the pressure of ensuring environmental sustainability became one of the greatest challenges for logistics firms (Kim et al., 2024). However, to add to the challenge, it must not be forgotten that these firms are also profit-oriented, which makes them reluctant to adopt the sustainability initiatives that do not promise clear and measurable financial returns. Sustainability initiatives in logistics are motivated by strategic intent and economic gains (Roy and Mohanty, 2023). This inherent tension between environmental responsibility and economic performance underscores the need to analyze green logistics not only as a sustainability imperative but also as a financial decision-making problem.

There are many financial implications of greening logistics, but the most immediate financial implication lies in its impact on cost structure. Just as with any initiative, there are two major categories of expenses that green initiatives typically involve, capital expenditure (CAPEX) and operating expenditure (OPEX). CAPEX in green logistics initiatives refers to the investments made to long-term and more sustainability-oriented assets. These assets could be renewable energy systems, energy-efficient warehouses, or eco-friendly transportation. However, studies in the field highlight that sustainable technologies in logistics require significant initial investment relative to traditional assets, complicating their implementation (Mumcu, 2025). While traditional logistics systems focus on the short-term cost efficiency, with a strong emphasis on minimizing upfront capital expenditures, green logistics, on the other hand, often requires higher initial investments (Szentesi & Nagy, 2024; Rastegardebidi, 2025). Firms must also account for the additional costs associated with sustainable packaging, waste management, and carbon offset initiatives. These expenses may discourage companies—particularly small and medium-sized enterprises—from adopting environmentally responsible logistics practices (Sahu, 2025).

When managing costs in logistics, it is important to realize that by lowering one category of logistics expenses, one might actually cause an increase in other cost components, which might end up raising total costs and have detrimental effects to the overall profitability (Muha, 2019). OPEX of green logistics includes the recurring costs associated with both operating and maintaining these initiatives. They may include expenses relating to energy consumption, maintenance of clean technologies, training and monitoring. The benefits gained from adopting green initiatives in logistics in the long-term, such as cost savings from improved energy efficiency and enhanced brand loyalty, which is part of their OPEX, often outweigh the initial investments, in other words, higher CAPEX. Green logistics significantly alters OPEX over the lifecycle of logistics assets. Energy-efficient vehicles consume less fuel or electricity per unit of output, while renewable energy installations reduce dependence on volatile energy markets. Similarly, optimized routing

and load management systems lower fuel consumption and labor costs. Over time, these operational efficiencies can generate substantial cost savings.

The ability to balance these short-term costs with long-term gains (i.e. higher CAPEX and lower OPEX) is therefore critical if a firm is seeking to integrate sustainability into their logistics operations without compromising its financial viability. Effective green logistics strategies require careful planning, targeted investment, and continuous optimization. Actors involved in logistics operations tend to see green logistics primarily as a means of internalizing the cost savings, while giving limited attention to the issue of external costs (Rodrigue et al., 2001).

From a financial perspective, this shift towards green logistics emphasizes the importance of using lifecycle cost analysis (LCCA) and total cost of ownership (TCO) approaches within such initiatives. The primary purposes of LCCA and TCO are similar and involves a comprehensive framework for estimating the total cost of an initiative over its entire life cycle (Tibben-Lembke, 1998; Durairaj et al., 2002). While green logistics may require higher initial capital expenditure, their cumulative operating costs are often lower, leading to favorable long-term cost profiles that make these evaluation frameworks more relevant (Onukwulu et al., 2021). Consequently, it is clear that comparing costs is not enough to understand green logistics initiatives. A more dynamic and time-based financial assessment is needed.

## **2.2. Impact on Financial Performance and Risk Profile**

Changes in cost structure inevitably affect financial performance (Agyabeng-Mensah and Tang, 2021). Although both LCCA and TCO tries to explain how greening logistics restructures the costs over time, they cannot fully explain the financial implications of such a transition. Green logistics does not just affect the cost dynamics, the process also has effects on cash flow generation, profitability, risk exposure, and hence, the overall financial performance of companies. Financial performance, in this context, can be defined as the utilization of all financial and non-financial resources, whether they are tangible or intangible, by businesses in order to achieve their financial objectives. When these financial objectives include the rationale behind establishing and sustaining these profit-oriented businesses, then it becomes critical that financial performance be measured, and the results reflected in the decision-making process (Agyabeng-Mensah et al., 2020). Therefore, financial performance considerations become inseparable from the strategic drivers that motivate firms' environmental responses.

Previous studies on businesses and their environmental motives have identified four key drivers of their responses. These were the role of legislation, reputational pressures from stakeholders, economic opportunities presented, and ethical motives. Together, these four drivers construct the framework to

explain why businesses are adopting either reactive or proactive approaches to conduct green logistics operations. It is also important to be able to understand how these choices affect the financial performances of businesses in the end. While legislative pressures generally are found to encourage businesses to pursue a more reactive and compliance-oriented responses to mitigating regulatory risks, in contrast, reputational pressures by stakeholders and ethical motivations were found to be more encouraging on the proactive responses. Economic opportunity, however, seems to provide the most direct connection between environmental initiatives and financial value generation (Bansal and Roth, 2000).

Green logistics also impacts firm-level financial performance through a set of interconnected mechanisms that go beyond short-term cost efficiency. By shaping operating margins, cash-flow stability, risk perceptions, and competitive positioning, green logistics initiatives influence both short-term financial metrics and long-term value creation. The magnitude and temporal realization of these benefits are reliant upon firms' strategic standing toward green logistics and the drivers underlying their environmental commitments (Baah et al., 2020).

### **2.2.1. Operating Margin Effects**

Operating profitability constitutes one of the most direct channels through which green logistics influences firm-level financial performance (Khoa and Nhung, 2020). Energy-related expenditures account for a substantial share of logistics operating costs, making firms particularly vulnerable to volatility in fuel and electricity prices (Jayamaha, 2006; Gorcun, 2017). When motivated by economic opportunity—such as improvements in fuel efficiency, energy savings, and operational optimization—green logistics initiatives generate persistent reductions in operating costs (McKinnon, 2012; Ostapenko et al., 2020; Kim et al., 2014). Investments in electric vehicle fleets, on-site renewable energy generation, and energy-efficient logistics facilities enable firms to partially decouple operating expenses from fluctuations in global energy markets (Jayamaha, 2006). Although such initiatives typically involve higher upfront capital expenditures, they tend to enhance operating margins once the investment phase is completed, particularly for high-mileage transportation fleets and energy-intensive logistics infrastructures (Anjanappa, 2025). By lowering exposure to energy price volatility, green logistics contributes to greater margin stability and strengthens the resilience of logistics firms against external economic shocks (Tarkun, 2025). Traditional logistics systems are therefore highly exposed to abrupt increases in fossil fuel prices, which can rapidly compress operating margins. Green logistics mitigates this exposure by reducing overall energy intensity and increasing reliance on renewable or relatively stable energy sources (Anser et al., 2020).

### 2.2.2. Cash-Flow Predictability and Stability

Green logistics also influences the volatility and predictability of operating cash flows, particularly when driven by legislative and regulatory pressures (Athanasios, 2018). Conventional logistics operations are highly exposed to fuel price fluctuations, as mentioned previously, and abrupt regulatory interventions, both of which introduce significant uncertainty into operating cash flows (Baah et al., 2023). By proactively aligning logistics activities with evolving environmental standards, businesses can mitigate compliance-related cost shocks, reduce exposure to energy price volatility, and improve overall environmental performance (Kalubanga and Mbekeka, 2024; Suraharta and Hendrasti, 2025). As a result, green logistics initiatives contribute to more stable and predictable cash-flow patterns, facilitating improved liquidity management in the short-term and strengthening firms' ability to plan long-term investments and meet financial obligations. These effects are particularly important in capital-intensive logistics operations, where cash-flow stability is critical for sustaining operational continuity and financing capacity.

### 2.2.3. Risk Premium and Cost of Capital Effects

Logistics businesses are increasingly exposed to regulatory and transition risks arising from climate policy developments, increasing emissions standards, and changing carbon pricing mechanisms (Sun et al., 2023). Businesses that continue to rely on carbon-intensive logistics assets face elevated risks related to future compliance costs, operational constraints, and potential asset obsolescence. In contrast, businesses that proactively adopt green logistics practices (GLPs) signal lower exposure to transition and regulatory risks, as well as reduced reputational vulnerability associated with environmental non-compliance (Van Snellenberg and Van de Peppel, 2002; Baah et al., 2021).

Capital market participants are increasingly incorporating these risk dimensions into their decisions involving investments and lending. Consequently, credible and well-communicated green logistics strategies may lower perceived business risk, resulting in a reduced equity risk premium and more favorable borrowing conditions. Over time, such improvements in risk perception can translate into a lower weighted average cost of capital (WACC), thereby amplifying the valuation effects of green logistics investments (Gniadkowska-Szymanska, 2025). Viewed through this lens, green logistics functions not only as an operational or environmental initiative but also as a strategic risk management mechanism, enabling firms to navigate the transition toward low-carbon logistics systems in a more stable and financially resilient manner.

#### **2.2.4. Revenue Growth and Market Access Effects**

Economic opportunity and reputational motivations significantly shape the revenue-related impacts of green logistics. As sustainability requirements become increasingly integrated into procurement policies and supplier evaluation criteria, logistics providers with credible decarbonization commitments are better positioned to access new markets and attract environmentally conscious customers (Chaabane et al., 2011; Baah et al., 2021). Businesses that adopt green logistics practices proactively are more likely to obtain preferred supplier status, secure longer-term contractual arrangements, and foster stronger customer relationships, particularly within export-oriented supply chains subject to strict environmental standards (Kawa and Pieranski, 2021; Wang et al., 2024; Roy and Mohanty, 2024). These advantages strengthen the economic case for green logistics by directly connecting environmental performance to revenue expansion and demand stability.

For these reasons mentioned, the four drivers proposed by Bansal and Roth (2000) provide a coherent explanation not only for businesses' engagement in green logistics but also for the mechanisms through which such engagement influences financial performance. While compliance-oriented responses primarily serve to limit downside exposure, strategies driven by economic opportunity and reputational considerations are more likely to deliver enduring financial gains through efficiency improvements, risk reduction, and stronger market positioning. From this standpoint, green logistics should be understood as a strategic financial choice embedded in long-term value creation rather than as an exclusively environmental or ethical initiative.

#### **2.3. From Cost Minimization to Long-Term Value Creation**

Traditional logistics decision-making has long been guided by a short-term cost minimization mindset, with managers prioritizing immediate operating cost reductions and limiting upfront capital expenditures (Ho et al., 2009; Micieta et al., 2015). Within this framework, green logistics initiatives are often viewed as financially unattractive because they involve higher initial investments and longer payback periods, which can temporarily depress short-term financial performance (Guo et al., 2020).

This perception, however, largely reflects the limitations of short-term evaluation methods. When assessed using long-term financial and valuation-based perspectives, green logistics emerges as a value-enhancing strategy rather than a cost burden. Prior studies show that improvements in resource efficiency, waste reduction, and supply chain integration can translate into sustained competitiveness, stronger operational performance, and enhanced firm value over time (Porter and van der Linde, 1995; Rao and Holt, 2005; Lee et al., 2011; Stentoft and Rajkumar, 2018). While environmental management

practices may initially increase investment and operating costs, these effects are often offset by recurring efficiency gains, including lower energy use, reduced waste treatment expenses, and cost savings from reverse logistics activities (Melnyk et al., 2002; Famiyet et al., 2018).

From a cash-flow perspective, green logistics investments generate long-term operating savings through reduced energy consumption, lower maintenance needs, and improved operational efficiency. When these benefits are evaluated over the economic life of logistics assets, their discounted value can outweigh higher upfront capital expenditures, highlighting the importance of cash-flow-based appraisal methods over static cost comparisons (Sun et al., 2023).

Beyond efficiency gains, green logistics also creates value by reducing risk. Sustainability-oriented logistics strategies lower exposure to regulatory uncertainty, energy price volatility, and reputational risk, contributing to more stable and predictable cash flows (Branco and Rodrigues, 2006; Gouda and Saranga, 2018; Zhang et al., 2020). In an increasingly uncertain global environment shaped by geopolitical and energy market risks (Caldara and Iacoviello, 2022), such stability enhances risk-adjusted returns and strengthens firms' long-term resilience. Green logistics investments further provide real option value by improving firms' ability to adapt to future regulatory and market changes, even if these benefits are not immediately visible in short-term accounting metrics (Issa et al., 2024).

Taken together, green logistics appears costly only when evaluated through a short-term cost lens. When viewed in terms of long-term cash flows, risk reduction, and operational resilience, it represents a strategic financial investment that supports sustainable value creation. Accordingly, the focus shifts from questioning the financial viability of green logistics to determining how such investments should be evaluated and justified using appropriate financial decision-making frameworks.

### **3. Green Logistics Investments and Appraisals: Is Green Logistics Financially Viable?**

Having established that green logistics can create long-term value when evaluated through net present value, risk-adjusted return, and resilience-based perspectives, the central issue shifts to its financial viability from an investment appraisal standpoint. Logistics firms operate under capital constraints, face competing investment opportunities, and are accountable to shareholders and lenders who require transparent and defensible justification for major capital expenditures. Consequently, green logistics initiatives must be assessed using systematic appraisal frameworks that translate sustainability objectives into measurable financial outcomes.

Green logistics investments are typically characterized by high upfront capital intensity, long asset lifecycles, and uncertain—yet potentially significant—operating benefits. Bowen et al. (2001) argue that firms are more likely to adopt green supply chain management (GSCM) practices when clear financial and operational benefits can be identified, even when the primary objective is to reduce the environmental impact of supply chain activities. Unlike conventional logistics investments, however, the financial performance of green logistics projects is shaped not only by internal efficiency gains but also by external factors such as energy price volatility, regulatory developments, carbon pricing mechanisms, and public incentives (Saeed et al., 2018; Jefimovaite and Vienazindiene, 2022). These features complicate traditional appraisal approaches, as short payback horizons or purely accounting-based metrics may fail to capture the full economic value generated over the lifecycle of green investments (Purwanti, 2023).

From an appraisal perspective, the financial viability of green logistics rests on three interrelated considerations.

- First, firms must clearly identify and classify green logistics investments—such as transportation assets, infrastructure upgrades, digital systems, and energy-related technologies—each of which exhibits distinct cost structures and risk profiles.

- Second, a comprehensive view of costs is required, encompassing not only acquisition and installation expenses but also operating, maintenance, compliance, and end-of-life costs.

- Third, investment evaluation must rely on capital budgeting techniques that are consistent with the long-term, risk-sensitive nature of green logistics projects.

Conventional appraisal tools, including payback period, net present value (NPV), and internal rate of return (IRR), therefore remain central to the evaluation of green logistics investments (Purwanti, 2023). However, their application must be adapted to reflect the specific characteristics of green projects. Cash-flow projections should incorporate lifecycle cost savings, carbon-related cash flows, and policy incentives, while discount rates should account for changes in risk exposure associated with reduced environmental and regulatory uncertainty. When applied in this manner, these tools enable decision-makers to determine whether green logistics investments satisfy required return thresholds and contribute positively to long-term firm value.

### **3.1. Categories of Green Logistics Investments**

Green logistics investments encompass a broad portfolio of assets and technologies that differ markedly in their cost structures, risk profiles, and financial implications.

- **Transportation-related investments**—including electric vehicles (EVs), hybrid fleets, hydrogen-powered trucks, and alternative fuel systems—represent the most visible component of green logistics transformation. These investments directly address emissions from freight transportation and last-mile delivery, which constitute one of the largest sources of carbon intensity in logistics operations. From a financial perspective, transportation investments are typically capital-intensive, requiring substantial upfront CAPEX, while offering long-term operating cost savings through lower fuel consumption, reduced maintenance costs, and, in some jurisdictions, tax credits or carbon-related incentives (Hackney and De Neufville, 2001; Odock et al., 2024).

- **Infrastructure-related investments** focus on logistics facilities such as warehouses, distribution centers, and intermodal hubs. These investments may involve advanced insulation, energy-efficient lighting systems, automation technologies, and on-site renewable energy generation (Mahmood et al., 2025). Although these investments also involve significant initial capital outlays, they are often characterized by more predictable cash flow benefits, stemming from lower energy expenses, enhanced asset lifecycles, and improved compliance with environmental regulations, making them particularly suitable for long-term financial evaluation using lifecycle-based methods (Xu et al., 2019). Importantly, such investments may also positively affect asset valuation by increasing the marketability and regulatory resilience of logistics real estate.

- **Digital and data-driven investments**—such as route optimization software, predictive analytics, digital twins, and real-time monitoring systems—represent a relatively less capital-intensive but highly scalable category. While their direct emission reduction impact is often indirect, these technologies improve asset utilization, reduce empty miles, and enhance energy efficiency across the logistics network (Liu et al., 2024). Financially, digital investments are distinguished by shorter payback periods, lower technological risk, and higher flexibility, making them attractive complements to heavy physical investments in vehicles and infrastructure (Vilaplana et al., 2025).

- Finally, **organizational and process-related investments**—such as employee training, sustainability reporting systems, and reverse logistics capabilities—support the effective implementation of green logistics strategies (Gruchmann, 2018). While these investments may not always involve large capital expenditures, they generate enabling benefits that are essential for realizing the full financial potential of green logistics initiatives.

Across these categories, green logistics investments differ substantially in terms of capital intensity, technological maturity, regulatory dependence, and exposure to operational and market risks. As a result, firms must design investment strategies that align with their operational scale, regulatory

environment, access to financing, and risk tolerance. Rather than pursuing isolated projects, effective green logistics strategies typically involve portfolio-based investment decisions, where transportation, infrastructure, and digital initiatives are jointly evaluated within a unified financial framework.

### **3.2. Comprehensive Cost Components of Green Logistics Investments**

Engelage and Borgert (2022) conceptualize green logistics as a multidimensional system that includes green transportation; loading and unloading; design and packaging; purchasing and storage; green production; reverse logistics; and green marketing. Together, these activities form an integrated framework through which environmental objectives are embedded into logistics operations. Effective management of these green logistics activities can generate substantial financial benefits for firms. Prior research suggests that such practices may enhance resource utilization, reduce inventory levels and space requirements, improve material efficiency, eliminate various forms of waste, and lower spoilage and obsolescence costs (Aronsson and Hüge-Brodin, 2006; Niwa, 2014; Lai et al., 2012). In addition, by strengthening market positioning and supporting access to environmentally sensitive customers, green logistics can contribute to revenue growth and profitability, thereby offsetting the higher upfront costs associated with ecological investments and process adaptations. At the same time, empirical studies consistently report both positive and negative cost impacts following the adoption of green logistics practices, underscoring the importance of accurately identifying and managing these cost elements as a prerequisite for sound managerial decision-making.

From a financial perspective, logistics costs can be broadly categorized into agricultural logistics costs, primary logistics costs, secondary logistics costs, export logistics costs, and administrative costs (Engelage and Borgert, 2022). While such classifications provide useful aggregate insights, investment appraisal requires a more granular and project-specific approach. At the project level, financial viability depends not on general cost trends but on the precise identification and timing of all cash inflows and outflows associated with a specific green logistics initiative over its economic life. Therefore, categorization of these costs changes.

The first major cost category consists of initial investment costs, including the acquisition of green logistics assets, installation and commissioning expenses, infrastructure modifications, and the integration of new technologies with existing logistics systems (Garg and Vemaraju, 2025). These costs are typically incurred upfront and often exceed those of traditional alternatives, making them highly visible and frequently decisive in capital budgeting decisions (Nicoletti and Appolini, 2024).

Beyond these initial costs, operating and maintenance costs must

be estimated over the asset's lifecycle. Green logistics investments often generate operating savings through reduced energy consumption, lower fuel dependency, and decreased maintenance intensity, as previously mentioned. However, they may also introduce new recurring costs related to software licensing, specialized maintenance services, data management, or workforce training (Abdi and Taghipour, 2019; Nijhavan et al., 2025). From an appraisal standpoint, these recurring cash flows must be explicitly modeled rather than treated as qualitative efficiency improvements.

A further set of costs arises from regulatory, compliance, and transactional requirements. Environmental monitoring, certification, reporting, and auditing obligations can introduce additional cash outflows, particularly during the early phases of implementation (Yang and Wang, 2025). Although proactive green logistics strategies may reduce long-term regulatory and transition risks, these compliance-related costs must be incorporated into project-level financial analysis to avoid understating total investment requirements.

Finally, terminal value considerations play an important role in determining overall project profitability. Green logistics assets may differ from conventional assets in terms of residual value, secondary market demand, or disposal constraints due to evolving regulatory and environmental standards (Gobbi, 2011). Accounting for salvage values, decommissioning costs, and potential refurbishment or reuse options ensures that the appraisal captures the full economic lifecycle of the investment.

Taken together, these cost components constitute the cash-flow foundation necessary for rigorous investment appraisal. Without a comprehensive, lifecycle-based identification of costs, subsequent financial evaluation techniques—such as net present value or internal rate of return—cannot reliably assess the financial viability of green logistics investments.

### **3.3. Payback Period, NPV, and IRR in Green Logistics Investment Appraisal**

With project-level cash flows clearly specified, the financial viability of green logistics investments can be assessed using established capital budgeting techniques. Among these, the payback period, net present value (NPV), and internal rate of return (IRR) are the most widely applied tools, each offering a distinct perspective on investment performance and risk.

The payback period measures the time required to recover the initial investment from net cash inflows (Zis et al., 2016). This metric is particularly useful for evaluating liquidity risk and the speed of capital recovery. However, its applicability to green logistics investments is limited. Such projects are typically characterized by high upfront capital requirements and benefits that

accrue gradually over long asset lifecycles. As a result, payback-based criteria tend to undervalue investments that generate substantial long-term economic benefits, as they ignore cash flows occurring beyond the recovery period and do not account for the time value of money (Rappaport, 1965). Consequently, the payback period should be interpreted as a supplementary indicator rather than a decisive investment criterion.

In contrast, the net present value (NPV) method provides a more appropriate and comprehensive framework for evaluating green logistics investments. By discounting expected cash flows over the full economic life of the project, NPV captures operating cost savings, efficiency improvements, and policy-related cash flows within a single value-based measure (Purwanti, 2023). A critical aspect of NPV analysis is the selection of an appropriate discount rate, which should reflect the project's risk profile, including changes in exposure to energy price volatility, regulatory uncertainty, and transition risk. When these factors are properly incorporated, NPV directly indicates whether a green logistics investment contributes to long-term firm value. Given the sensitivity of NPV to discount rate assumptions, even small variations can materially affect valuation outcomes, underscoring the importance of accurately estimating risk-adjusted discount rates (Hussain et al., 2025).

The IRR complements NPV by expressing investment performance as a rate of return that can be compared with hurdle rates or alternative investment opportunities. IRR represents the discount rate at which the project's NPV equals zero and is particularly useful in contexts where capital is rationed, or firms must prioritize among competing logistics investments. Green logistics projects with relatively high IRRs may appear especially attractive to decision-makers, as they signal returns exceeding those of conventional investments (Purwanti, 2023). Nevertheless, caution is required when interpreting IRR for green logistics projects with long lifecycles or non-standard cash-flow patterns. In such cases, IRR may fail to reflect project scale, risk differentials, or delayed investment effects, potentially leading to misleading conclusions if used in isolation (Fouche and Crawford, 2017).

In practice, the financial justification of green logistics investments requires the joint application of these appraisal techniques. The payback period addresses short-term liquidity and capital recovery concerns, NPV evaluates absolute value creation over the project lifecycle, and IRR facilitates relative comparison across investment alternatives. When applied together and grounded in lifecycle-based cash-flow estimation, these tools translate the long-term value logic of green logistics into robust and actionable investment decisions.

#### **4. Carbon Credits and Environmental Incentives: How Does Government Policy Initiatives Affect Cash Flows?**

Corporate environmental commitment requires the backing of a stable and effective regulatory framework in order to translate intention into sustained action. Although capital budgeting tools allow firms to assess green logistics investments on the basis of projected internal cash flows, these evaluations are incomplete if external policy instruments—such as carbon pricing schemes, environmental regulations, and government incentives—are not taken into account. The adoption of green logistics practices frequently involves additional capital outlays, greater operational complexity, and enhanced skill requirements, often accompanied by organizational adjustments and behavioral change within the firm (Engelage and Borgert, 2022). Consequently, regulatory conditions and policy incentives play a decisive role in shaping both the cost dynamics and risk exposure of green logistics projects and must therefore be embedded within comprehensive financial appraisal models.

Empirical research further highlights the importance of the broader macro-institutional environment. Using the Best–Worst Method, Ahmad et al. (2017) identify political and economic stability as critical determinants influencing sustainability-oriented investment decisions. This finding underscores that green logistics investments are not evaluated in isolation; rather, firms’ willingness to commit capital depends heavily on the predictability, credibility, and enforcement strength of the regulatory environment in which they operate.

For this reason, the financial implications of green logistics investments cannot be fully understood without a comparative assessment of regulatory regimes across jurisdictions. The European Union’s Green Deal represents a mature, binding, and increasingly stringent climate governance framework, whereas Türkiye’s green transition architecture remains in a formative but rapidly converging phase. For logistics firms operating across borders—or integrated into EU-oriented value chains—this divergence and gradual alignment have material consequences for cost structures, contract design, and capital budgeting decisions.

##### **4.1. Carbon Pricing and Its Cash-Flow Implications**

Sustainability-oriented supply chain management inevitably introduces additional cost considerations and operational constraints. The implementation of market-based carbon control instruments—such as carbon taxes and emissions trading schemes—further increases the financial and managerial complexity faced by logistics firms. From an economic standpoint, pricing carbon emissions is widely recognized as an efficient policy instrument for achieving meaningful reductions in greenhouse gas emissions, as it embeds

environmental externalities into market decision-making (Ramudhin et al., 2010). By attaching a monetary cost to emissions, carbon pricing transforms environmental impact into a direct financial variable that must be incorporated into business planning (Ji et al., 2018).

Carbon pricing frameworks are generally categorized into two principal models: carbon taxation and emissions trading systems. More comprehensively, Narassimhan et al. (2018) distinguishes among three broad approaches: cap-and-trade mechanisms (emissions trading systems), carbon taxes, and hybrid models combining elements of both. A carbon tax imposes a predetermined fee on carbon-intensive fuels or activities, thereby increasing production and transportation costs in proportion to emissions levels. Its objective is to incentivize firms to reduce emissions through efficiency improvements, cleaner technologies, or process innovation (Tsai, 2020). In contrast, emissions trading systems establish a fixed emissions ceiling and allocate tradable allowances. Firms that emit below their allocation may sell excess permits, while those exceeding limits must purchase additional allowances, with the market determining the prevailing carbon price (Ji et al., 2018).

Within Europe, the European Union Emissions Trading System (EU ETS) represents the most comprehensive and institutionalized example of a cap-and-trade system. By setting emission caps and enabling allowance trading, the EU ETS effectively incorporates carbon costs into energy and fuel prices, thereby influencing the operating expenses of logistics providers (Lagouvardou and Psaraftis, 2022). Recent expansions of the system, including ETS II, extend carbon cost exposure to additional sectors, increasing indirect financial effects for logistics firms through fuel suppliers and energy-intensive infrastructure (Hintermann et al., 2016). Under such a regime, carbon pricing becomes an embedded cost driver rather than a peripheral policy consideration.

Financially, carbon pricing alters operating cash flows by raising the marginal cost of carbon-intensive logistics activities. Firms dependent on diesel-powered fleets and inefficient facilities are particularly vulnerable to rising or volatile carbon prices, which increase operating expenditure and introduce earnings variability. Conversely, investments in low-emission transport solutions, energy-efficient buildings, and renewable energy integration reduce emissions intensity and therefore limit exposure to carbon price fluctuations (Trinks et al., 2022; Sun et al., 2023). By lowering sensitivity to carbon market dynamics, green logistics initiatives enhance cash-flow stability and improve the long-term financial attractiveness of decarbonized logistics systems, especially when evaluated using risk-adjusted valuation models.

In Türkiye, although a fully operational emissions trading system has yet to be implemented, carbon-related financial pressures are already emerging through policy signaling and international market integration. The country's Green Transition Framework and ongoing preparations for a domestic emissions trading mechanism indicate a regulatory trajectory toward formal carbon cost internalization. Furthermore, logistics firms operating within EU-linked supply chains are indirectly exposed to European climate instruments such as the Carbon Border Adjustment Mechanism. Consequently, early adoption of green logistics strategies functions as a risk-mitigation tool, allowing firms to anticipate and manage future carbon-related cost increases and compliance requirements. Even in advance of full domestic implementation, carbon pricing expectations influence capital allocation decisions, risk assessments, and long-term financial planning.

#### **4.2. Carbon Credits as Revenue and Risk-Management Instruments**

Global concern over climate change led to the formal establishment of carbon markets under the Kyoto Protocol in 1997, marking a pivotal shift in how environmental externalities are addressed within economic systems (Macit, 2025). By assigning a monetary value to greenhouse gas emissions, carbon markets transformed environmental performance into a financial variable, directly linking emission levels to corporate cost structures and investment decisions.

A carbon credit represents a tradable authorization to emit one metric tonne of carbon dioxide equivalent (CO<sub>2</sub>e). In practical terms, one credit corresponds to either the reduction or removal of one tonne of greenhouse gas emissions. Carbon credits are generally categorized into Certified Emission Reductions (CERs)—issued under regulated compliance mechanisms—and Voluntary Emission Reductions (VERs)—generated in voluntary markets (Anukwonke and Abazu, 2022). Due to differences in regulatory oversight and verification rigor, VERs typically trade at lower prices than CERs (Abdallah et al., 2012).

Carbon markets function as economic systems that incentivize emission reduction by allowing firms to trade allowances or credits. They can be broadly divided into compliance markets, which operate under binding regulatory frameworks such as the European Union Emissions Trading System (EU ETS), and voluntary markets, which enable firms to offset emissions beyond mandatory requirements. The EU ETS remains the world's largest permit-based carbon trading platform, while mechanisms such as the Clean Development Mechanism (CDM) have historically played a major role in generating tradable emission credits (Mehmood et al., 2025).

The underlying economic principle of carbon trading is cost efficiency. Firms with lower marginal abatement costs can reduce emissions more

economically than others. Trading therefore ensures that emission reductions occur where they are most financially efficient, minimizing overall compliance costs (Abdallah et al., 2012). This flexibility allows firms either to invest internally in emission-reduction technologies or to purchase credits from other market participants, depending on relative cost considerations.

Government intervention remains central to the functioning and credibility of carbon markets. Authorities influence market stability through price ceilings and floors, permit reserve mechanisms, and regulatory oversight (Ji et al., 2018). By releasing or withdrawing allowances, governments can moderate excessive price fluctuations and maintain market confidence. These policy actions directly affect carbon price dynamics, which in turn influence firms' operating costs, investment timing, and strategic planning. For logistics companies, carbon markets create both financial obligations and financial opportunities. On the cost side, carbon pricing increases the operational expenses of emission-intensive logistics activities, particularly in fuel consumption and energy use. On the revenue side, firms that successfully reduce emissions—through fleet electrification, alternative fuels, energy-efficient infrastructure, or digital optimization—may generate tradable carbon credits.

From a capital budgeting perspective, these credits represent potential cash inflows that can enhance the NPV and IRR of green logistics investments when incorporated into financial projections. In addition, carbon credits function as risk management instruments (Trouwloon et al., 2023). Firms that generate or accumulate credits can partially hedge against future increases in carbon prices or stricter regulatory standards (Palazzi et al., 2024). This hedging capability reduces downside exposure and stabilizes projected cash flows, especially for firms operating across jurisdictions with diverse climate policies.

However, carbon allowance prices are determined by supply-demand dynamics and are subject to volatility. Unlike conventional financial assets such as bonds or equities, carbon allowances do not provide periodic income streams; their financial return depends on resale value and market conditions (Demiralay et al., 2022). Consequently, carbon-related revenues should be modeled conservatively in financial appraisals, supported by sensitivity analysis to account for price uncertainty and regulatory risk.

In Türkiye, voluntary carbon markets currently play a more significant role, allowing logistics firms to monetize emission-reduction efforts and improve project-level financial performance (Ozcan, 2022). As national carbon pricing mechanisms evolve and integration with EU climate frameworks deepens, carbon-related cash flows are likely to become increasingly material in capital budgeting decisions.

Ultimately, carbon markets offer firms two strategic pathways: they may acquire credits to offset emissions externally or invest in cleaner technologies to reduce emissions internally (Maqsoom et al., 2025). While credit purchases provide short-term flexibility, internal green investments often generate additional operational efficiencies and long-term strategic benefits. Both approaches, however, integrate environmental performance directly into financial outcomes. Despite price volatility and regulatory complexity, carbon credits increasingly serve as a bridge between environmental responsibility and financial performance, embedding climate considerations into both cash-flow projections and risk management strategies.

### **4.3. Government Incentives and Public Support Mechanisms**

Beyond carbon pricing and emissions trading systems, governments deploy a wide range of policy instruments to accelerate the adoption of green logistics practices (McKinnon, 2010). These instruments include capital grants, direct subsidies, tax incentives, accelerated depreciation schemes, concessional lending arrangements, and public guarantees. Such measures are primarily designed to address two major barriers to green investment: high upfront capital expenditures and technological uncertainty (Aziz and Abidin, 2021; Makhmudov and Karshiev, 2024). By lowering entry costs and mitigating risk, these incentives aim to realign private financial incentives with broader environmental objectives.

In the European Union, these policy tools operate within the broader framework of the European Green Deal. Under this framework, green logistics initiatives may receive financial support that directly enhances project-level performance by reducing effective capital outlays, increasing after-tax cash flows, or lowering financing expenses. From a capital budgeting standpoint, such support improves financial feasibility by shortening payback periods, increasing net present values (NPVs), and strengthening internal rates of return (IRRs). Beyond these immediate cash-flow benefits, however, EU policy instruments also send long-term regulatory signals. By demonstrating sustained political commitment to decarbonization, they reduce policy uncertainty and mitigate transition risk, thereby strengthening the strategic attractiveness of green logistics investments (Gomez, 2021).

This reduction in regulatory uncertainty has implications that extend beyond individual project cash flows. Climate policy frameworks influence how investors assess firm-level risk and long-term sustainability (Agrawal et al., 2025). As carbon exposure becomes increasingly measurable and regulated, it is incorporated into financial risk models and required rates of return, ultimately affecting firms weighted average cost of capital (WACC) (Meneses Ceron et al., 2024). In the EU, explicit carbon pricing under the EU ETS, together with trade-related instruments such as the Carbon Border

Adjustment Mechanism (CBAM), provides investors with clearer information about future regulatory trajectories (Perdana and Vielle, 2025). This regulatory clarity enables capital markets to more precisely quantify transition risk.

As a result, firms that proactively reduce carbon exposure through green logistics investments are increasingly perceived as lower-risk entities. Strong decarbonization strategies signal improved capacity to manage environmental, regulatory, and reputational risks—capabilities that are particularly valuable in interconnected global markets (Benson et al., 2010). For logistics firms, reduced exposure to carbon price volatility and compliance risk can lead equity investors to demand lower risk premia, while lenders may offer more favorable borrowing terms (Ahmed et al., 2025). Improvements in both the cost of equity and the cost of debt contribute to a lower WACC, thereby enhancing firm valuation, especially in capital-intensive logistics operations where long-term cash flows are highly sensitive to discount rates.

A similar, though structurally different, dynamic is emerging in Türkiye. Even in the absence of a fully operational domestic emissions trading system, investors increasingly engage in anticipatory risk pricing. Financial institutions differentiate logistics firms based on their preparedness for future carbon regulation and their continued integration within EU-oriented supply chains (Aydın, 2025). Firms that demonstrate credible and forward-looking green logistics strategies are perceived as more resilient to regulatory tightening and cross-border carbon measures, which can translate into improved access to capital and more favorable financing conditions over time (Kim et al., 2024).

Taken together, these developments illustrate that the financial consequences of climate policy are transmitted through two interrelated channels. First, policy instruments directly affect operating and investment cash flows through carbon costs and incentives. Second, and more structurally, they shape investor perception and risk assessment, influencing required returns and the cost of capital. Consequently, green logistics performance is evaluated not only through operational efficiency or compliance metrics, but also through its contribution to ESG standing and its effect on firm valuation.

## **5. ESG: How Do Markets React to Green Logistics?**

The progressive integration of carbon pricing mechanisms and environmental regulation into financial systems has fundamentally altered the role of environmental performance in corporate evaluation. What was once regarded primarily as a compliance obligation has evolved into a strategic factor influencing firm valuation. Companies are increasingly expected to fulfill broader social and environmental responsibilities during their operational activities—responsibilities that are now systematically assessed through Environmental, Social, and Governance (ESG) criteria. Growing investor interest in sustainable and long-term investment opportunities has

reinforced this shift, as firms demonstrating strong ESG performance are often viewed as more resilient and better positioned for future regulatory and market developments (Rodionova et al., 2022).

In the logistics sector, ESG performance is closely intertwined with operational structure. The environmental dimension focuses on minimizing the ecological footprint of supply chain activities, encompassing emissions intensity, fuel efficiency, renewable energy use, waste management, and resource optimization across transport and warehousing operations. Given the inherently energy-intensive nature of logistics services, environmental indicators frequently represent the most financially material ESG metrics in this industry. This relevance is further strengthened by expanding regulatory frameworks that increasingly hold firms accountable not only for their direct emissions but also for environmental impacts throughout their supply chains.

The social dimension of ESG highlights the human and relational aspects of supply chain management. It includes labor standards, occupational health and safety, stakeholder engagement, and supply chain transparency. For logistics providers operating within global value chains, social performance directly influences relationships with multinational customers that impose sustainability standards across procurement networks. Technological advancements, including blockchain-based traceability systems and digital monitoring tools, are further enhancing transparency and enabling firms to verify compliance with ethical labor practices throughout complex supply networks.

The governance dimension refers to the structures and processes that guide corporate decision-making and oversight. Within supply chain contexts, governance includes board-level supervision of sustainability strategies, transparent emissions reporting, risk management systems, and executive accountability mechanisms. Effective governance ensures that environmental and social objectives are integrated into corporate strategy rather than treated as peripheral initiatives. Although global supply chains are often fragmented and challenging to monitor, digital management systems increasingly enable real-time tracking and enforcement of governance standards (Leogrande, 2024).

Collectively, these ESG dimensions convert sustainability performance into measurable indicators that investors use to evaluate long-term resilience and risk exposure. Investor influence has emerged as one of the primary drivers behind ESG adoption within supply chains (Das, 2024). Investors increasingly recognize that firms with robust environmental, social, and governance systems are better equipped to manage regulatory risk, protect reputation, and sustain profitability (Malik et al., 2025). As carbon pricing and climate regulations become more institutionalized, ESG metrics function

as condensed signals through which markets assess transition readiness and strategic adaptability.

Green logistics initiatives therefore translate directly into improvements in ESG performance. Emission reductions enhance environmental ratings, increased supply chain transparency strengthens social credibility, and structured governance frameworks improve oversight quality. These ESG enhancements increasingly affect capital allocation decisions and financing conditions. The financial implications of ESG performance are most clearly reflected in its influence on the firm's cost of capital. As previously discussed, climate policy affects both expected cash flows and investor perception. ESG performance serves as the channel through which these policy-related risks are incorporated into capital market pricing. From a corporate finance perspective, firm value is determined by expected future cash flows discounted at the weighted average cost of capital (WACC). ESG performance affects both elements of this valuation framework. First, strong ESG performance contributes to greater cash-flow stability. Firms with credible decarbonization strategies face reduced regulatory penalties, lower exposure to carbon price volatility, and diminished reputational risk (Tvinnereim and Mehling, 2018). This enhanced predictability improves earnings stability and reduces downside risk in valuation assessments.

Second, ESG performance influences the discount rate itself by affecting both the cost of equity and the cost of debt. Firms with weak environmental performance may be perceived as more exposed to transition risk, regulatory uncertainty, and potential asset obsolescence, leading investors to demand higher risk premia. In contrast, logistics firms that proactively invest in green fleets, energy-efficient infrastructure, and transparent sustainability reporting signal reduced long-term risk. Lower perceived transition risk can reduce the equity risk premium, thereby decreasing the cost of equity. Even relatively small reductions in required return can significantly increase firm valuation in capital-intensive industries.

Debt markets reflect similar considerations. Lenders increasingly incorporate environmental exposure into credit risk assessments. Firms demonstrating credible green logistics strategies may benefit from improved credit ratings, narrower loan spreads, and access to sustainability-linked financing arrangements. Reduced perceived default risk and improved regulatory alignment can lower borrowing costs and enhance refinancing opportunities (Postiglione et al., 2024).

Consequently, green logistics investments generate financial value not only through operational efficiency gains but also by influencing how capital markets evaluate risk. ESG performance acts as the mechanism linking environmental strategy to financing conditions and overall firm valuation.

It is important to recognize that the financial benefits of ESG integration typically emerge over extended time horizons. Pro-environmental and governance initiatives rarely produce immediate accounting gains; instead, their impact becomes visible through gradual improvements in risk management, strategic positioning, and operational resilience. Managers should therefore approach ESG implementation as a long-term strategic investment rather than a short-term operating expense. Although sustainability policies and ESG reporting may not yield instant financial returns, they significantly enhance firms' capacity to generate stable operating profits and sustain long-term value creation (Gniadkowska-Szymanska, 2025).

## **6. Financing the Transition**

Successful green transformation requires substantial capital investment, which can be particularly challenging for firms with elevated risk profiles or limited credit capacity. Because green logistics projects are often capital-intensive and long-term in nature, financing decisions become strategically significant rather than purely operational choices. The selection between internal funding, conventional debt, capital market instruments, or hybrid financing structures directly influences leverage, liquidity, risk allocation, and ultimately the firm's weighted average cost of capital. As sustainability considerations increasingly shape corporate strategy, financial markets have responded by developing specialized instruments designed specifically to support environmentally responsible investments.

Among these emerging mechanisms, Green Supply Chain Finance (GSCF) represents an important evolution in the integration of sustainability and financial management. Unlike traditional financing models that evaluate firms primarily on creditworthiness and collateral, GSCF embeds environmental criteria into supply chain financing arrangements while preserving efficient flows of capital, goods, and information (Huang et al., 2024). In doing so, it extends sustainability incentives beyond individual firms to entire supply networks. However, the practical implementation of GSCF remains complex. Aligning environmental performance targets with financial incentives requires coordination among multiple stakeholders, while regulatory fragmentation and inconsistent ESG standards can limit its effectiveness. These structural challenges underscore that financing green logistics is not merely a matter of capital provision, but of systemic alignment across supply chain actors.

Closely related to GSCF, green credit financing has emerged as a more targeted approach to addressing financial constraints associated with environmental investments. While GSCF focuses on supply chain integration, green credit finance operates primarily through preferential lending mechanisms that reward sustainable corporate behavior. By offering

reduced interest rates, extended maturities, or improved lending conditions for environmentally responsible projects, green credit schemes help firms overcome the initial financial barriers to green transformation (Zhan and Wu, 2024). At a broader level, the expansion of green credit markets reflects a global shift toward embedding environmental risk assessment within mainstream banking practices. In this sense, green credit financing acts as a bridge between policy-driven sustainability goals and private sector capital allocation.

Moving from banking instruments to capital markets, green bonds represent a more formalized and standardized financing channel. Whereas green credit primarily operates within loan markets, green bonds allow firms to access a wider pool of institutional investors seeking ESG-aligned assets. A green bond is a debt instrument whose proceeds are exclusively dedicated to financing or refinancing eligible environmentally beneficial projects. Compared to conventional bonds, green bonds typically involve enhanced transparency and sustainability reporting requirements. For logistics firms, issuing green bonds not only facilitates funding for large-scale projects such as fleet electrification or energy-efficient infrastructure, but may also broaden the investor base and strengthen reputational standing (Bhutta et al., 2022). In some cases, strong investor demand for sustainable assets can contribute to more favorable pricing conditions.

Taken together, these financing instruments illustrate a progressive embedding of sustainability principles into corporate funding structures. What begins as a regulatory or operational imperative ultimately reshapes how capital is allocated and priced. Green logistics transformation is therefore financed through a combination of traditional and sustainability-oriented instruments, each influencing risk distribution and capital costs in different ways. The overall effectiveness of these tools depends on regulatory clarity, credible ESG performance, and coordinated stakeholder engagement—factors that collectively determine both access to capital and its cost.

### **Conclusion**

Taken together, this chapter has demonstrated that green logistics represents not merely an operational shift but a comprehensive financial transformation. It reshapes cost structures, stabilizes cash flows, reduces regulatory and transition risk, interacts with carbon markets, influences ESG-based investor perception, and alters the cost of capital. When evaluated through appropriate capital budgeting frameworks and supported by well-designed financing structures, green logistics can move beyond short-term cost considerations to become a strategic driver of long-term value creation.

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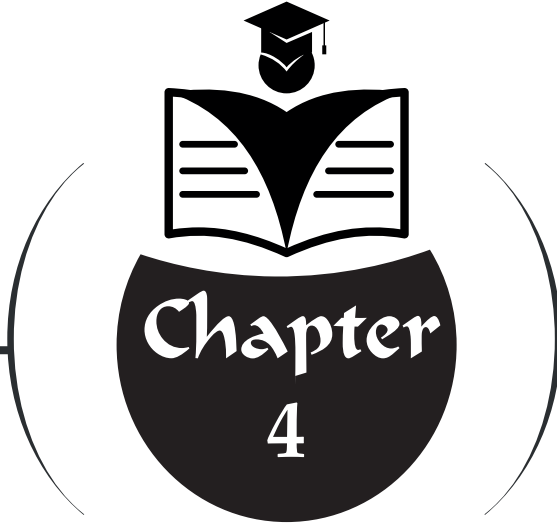
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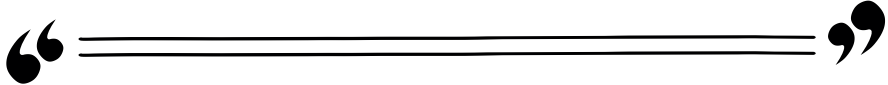
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## **PROCESS OPTIMIZATION AND EFFICIENCY ANALYSIS IN GREEN LOGISTICS**



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## 1. Introduction

Climate change, volatile energy prices, supply chain disruptions, and tightening regulation have shifted logistics from a narrow “cost minimization” function into a strategic domain where emissions, energy, service level, and risk must be managed simultaneously. The temperature-limitation goals of the Paris Agreement and countries’ Nationally Determined Contributions (NDCs) are accelerating the expectation that firms measure and reduce value-chain emissions—especially Scope 3, where logistics typically constitutes a material share (UNFCCC, 2015). In this transformation, logistics plays a pivotal role because transport and warehousing decisions simultaneously shape customer service performance and directly drive fuel consumption, carbon intensity, local air pollutants, and system resilience. The IPCC’s Sixth Assessment Report (AR6) emphasises that transport decarbonisation requires bundled interventions—demand management, modal shift, vehicle and energy technologies, and system-level efficiency measures—showing why “single-lever” solutions often underperform in practice (IPCC, 2022).

From an operations perspective, green logistics is not “a list of sustainability practices.” It is an end-to-end process engineering and decision-design problem spanning network configuration, warehousing operations, transport planning, packaging, returns, and information flows. A foundational reference in the field, *Green Logistics: Improving the Environmental Sustainability of Logistics*, strengthened this view by systematically linking logistics decisions to environmental impacts and pushing performance evaluation beyond the traditional cost–service trade-off (McKinnon, Browne, Whiteing, & Piecyk, 2015). The key implication for both researchers and practitioners is clear: meaningful improvement requires redesigning the decision logic of logistics processes—how they are planned, controlled, measured, and continuously improved. Traditional logistics operations are frequently managed through functional silos: procurement, warehousing, and distribution optimise their own local targets. Green logistics challenges this structure because environmental outcomes depend on system interactions, not isolated improvements. For instance, a warehouse objective to “pick faster” may push toward smaller batch sizes and higher dispatch frequency; if this triggers more trips and lower vehicle fill rates, transport emissions can rise even while warehouse productivity improves. Likewise, increasing delivery speed—especially in e-commerce—often reduces consolidation opportunities and increases vehicle-kilometres travelled, potentially worsening carbon intensity. The IPCC highlights that digitalisation and service acceleration can produce mixed effects on transport demand and emissions; therefore, technology adoption alone does not guarantee environmental gains unless the underlying processes are redesigned (IPCC, 2022).

Accordingly, green logistics processes should be analysed and managed

across three decision layers, each with distinct leverage points and performance consequences:

- Strategic layer (network design and capacity). Facility location and the number of depots, cross-docking design, allocation of customer regions, and modal choice (road–rail–sea–intermodal) define the structural “emissions potential” of the system. Operations Research (OR) literature repeatedly shows that design decisions can dominate long-term cost and emissions, and that system-level redesign often amplifies the benefits of later operational improvements (Dekker, Bloemhof, & Mallidis, 2012).

- Tactical layer (planning). Demand forecasting, inventory policies, shipment consolidation, routing and time-window planning, fleet composition (conventional vs. alternative fuels vs. EVs), and intermodal planning translate strategy into executable plans. Many “green gains” are achieved here because tactical rules determine fill rates, trip frequency, and avoidable kilometres.

- Operational layer (execution and control). Loading plans, driving style and speed profiles, warehouse energy management, pick/put-away routes, returns handling, and real-time replanning determine whether planned savings are realised. Execution quality is also where service constraints and variability become most visible.

Across these layers, “efficiency” cannot be reduced to a single indicator. Green logistics is inherently multi-objective: cost, lead time, service reliability, emissions, energy consumption, and operational risk interact. Consequently, multi-objective optimisation has been central to green logistics research from early stages, reflecting the need to balance outcomes rather than optimise one at the expense of others (Sbihi & Eglese, 2010; Dekker et al., 2012).

Green logistics typically contains two complementary questions:

The optimisation question: *Which combination of decisions (network, routing, inventory, capacity, mode choice, scheduling) best meets specified objectives under constraints?*

The efficiency question: *How effectively does the current operation (facility, route, fleet segment) convert inputs into outputs relative to comparable units, and where is the improvement potential?*

Optimisation is strong at producing the “best plan” for a defined model and scenario. Efficiency analysis is strong at benchmarking actual performance, identifying underperforming units, and quantifying improvement targets. When used together, these approaches create a practical improvement loop: optimisation supports redesign, while efficiency analysis supports diagnosis and prioritisation. From an OR standpoint, green logistics can be viewed as the integration of environmental dimensions into classical supply chain decision

models. A seminal review by Dekker et al. organises OR contributions to green logistics across design–planning–control and clarifies how embedding emissions into decision models creates new problem structures and solution needs (Dekker et al., 2012). Complementing this, Sbihi and Eglese stress the combinatorial nature of many green logistics problems—reverse logistics, waste management, vehicle routing and scheduling—explaining why algorithmic and computational tools are essential (Sbihi & Eglese, 2010).

In efficiency analysis, “output” is not merely delivered volume. It includes on-time delivery, damage rates, customer satisfaction proxies, emissions per ton-kilometre, warehouse energy intensity, and capacity utilisation. This richer view raises two practical issues that directly affect the credibility of any analysis:

- Standardisation of measurement. Emissions results depend on boundary definitions and computation method (e.g., tank-to-wheel vs. well-to-wheel; transport chain scope; data quality assumptions). Without a consistent method, improvement claims are not comparable over time or across units.
- Comparability under heterogeneity. Warehouses and routes differ in demand patterns, geography, time-window strictness, and service requirements. The challenge is to build fair comparisons and avoid penalising units serving intrinsically harder conditions.

Because of these issues, the field increasingly relies not only on internal KPIs but also on internationally recognised standards and sector frameworks that improve comparability and auditability.

The success of green logistics process optimisation depends on robust and transparent measurement. Two widely adopted references are particularly influential in logistics emissions accounting:

- ISO 14083:2023. This standard provides a common methodology for quantifying and reporting greenhouse gas emissions arising from transport chain operations, supporting consistent boundaries and reporting logic (ISO, 2023).
- GLEC Framework (Smart Freight Centre). This sector framework consolidates practical approaches for logistics emissions calculation and reporting; its updated versions have expanded scope and usability for real operations (Smart Freight Centre, 2023).

These references matter for optimisation models for two reasons. First, they determine how the emissions component included in objective functions or constraints is generated—without method consistency, scenario results are not comparable. Second, they align technical results with corporate reporting and assurance expectations, increasing the likelihood that an “optimal

plan” will be accepted and implemented rather than rejected on governance grounds.

Since the focus of this book chapter is process optimisation, it is useful to organise green logistics decision problems through a process lens:

- Transport and distribution optimisation (route–speed–load–time). Classical vehicle routing transforms when energy and emissions are explicitly considered. The Pollution-Routing Problem (PRP) introduced by Bektaş and Laporte highlights that emissions depend on speed and load, not only distance; therefore, “shortest path” is not necessarily “lowest emissions.” PRP-type models show that many green improvements come from planning levers—consolidation, time-window design, speed management, and fill-rate control—rather than technology change alone (Bektaş & Laporte, 2011).

- Warehousing and handling processes (energy–layout–picking). Warehouses can behave like energy-intensive production systems through lighting, HVAC, automation, and equipment. Process optimisation therefore includes layout design, picking route optimisation, equipment choices, and energy management. The green logistics literature treats warehousing impacts (energy use, land use, equipment) as a core component of environmental performance, not a secondary detail (McKinnon et al., 2015).

- Inventory–transport interaction (consolidation and batch size). Larger batches improve fill rates and reduce trips but increase inventory holding and obsolescence risk; smaller batches improve responsiveness but can raise trip frequency and emissions. This cross-process trade-off is one of the clearest examples of why green logistics must be treated as a system problem, and why planning decisions sit at the centre of environmental performance (Dekker et al., 2012).

- Reverse logistics and circularity (returns–recovery–reuse). Green logistics includes not only forward flows but also returns and recovery networks. Integrated models that jointly plan forward and reverse flows have been proposed early in the green supply chain literature, often using multi-objective programming to balance cost, service, and environmental impact (Sheu, Chou, & Hu, 2005).

- Digitalisation and decision support (visibility–analytics–optimisation). When emissions measurement, routing, warehouse management, and order promising operate in a shared data ecosystem, continuous improvement becomes feasible. Yet the IPCC notes that digitalisation can both reduce and increase transport demand; for example, service acceleration can raise demand and undermine consolidation. Digitalisation is not automatically “green”—it becomes green when paired with process design choices that control demand growth and improve system efficiency (IPCC, 2022).

Green logistics process optimisation is increasingly a matter of compliance and competitiveness, not only corporate responsibility. The EU's Sustainable and Smart Mobility Strategy proposes a roadmap for transforming European transport toward sustainability and smartness, creating practical pressures on firms through reporting expectations, fleet transition signals, intermodal initiatives, and urban logistics constraints (European Commission, 2020). At the same time, standardised emissions accounting frameworks (ISO 14083; GLEC) enable logistics service providers to differentiate via transparency and demonstrable improvement—turning measurement and optimisation capability into a market asset (ISO, 2023; Smart Freight Centre, 2023). Another driver is the recognition that value-chain emissions can be far larger than direct operational emissions, pushing logistics from an operational concern into the strategic agenda of top management—especially when customers and investors demand quantified reductions and credible pathways (UNFCCC, 2015; IPCC, 2022).

Rather than presenting green logistics as a catalogue of practices, this chapter develops a coherent framework built around process optimisation and efficiency analysis. It addresses four practical questions:

- How can green logistics processes be mapped, and which decision points dominate environmental performance?
- How should optimisation objectives and constraints be formulated, and how should emissions/energy be measured under recognised standards?
- How can efficiency analysis benchmark performance among comparable units and identify where improvement potential is concentrated?
- How can multi-objective outcomes (cost–service–emissions) be structured and communicated to decision-makers as implementable solution sets?

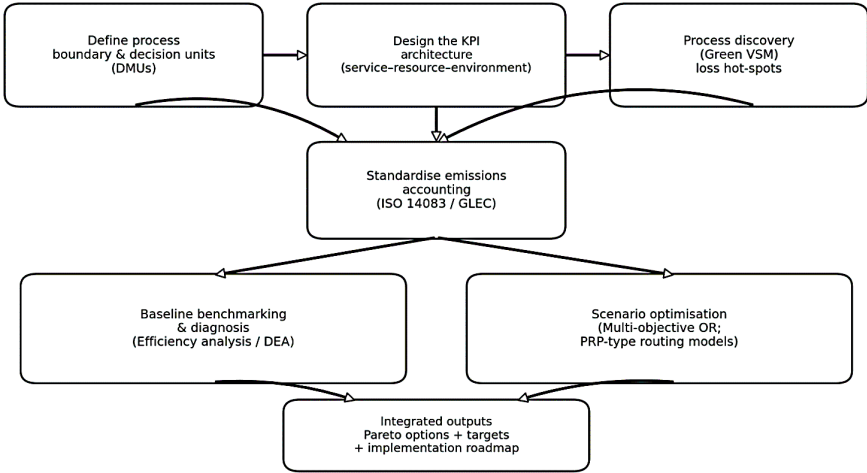
By integrating the analytical depth of OR and green supply chain research with contemporary standards and policy direction, the chapter aims to equip readers with an end-to-end design–implement–measure–improve loop.

## **2. An Integrated Framework for Process Optimisation and Efficiency Analysis in Green Logistics**

This book chapter is not centred on defining green logistics in general terms; instead, it focuses on building an actionable analytical framework that improves the environmental and operational performance of logistics processes simultaneously. Figure 1 summarises the integrated workflow proposed in this section. The framework starts by defining clear process boundaries and decision-making units (DMUs), then establishes a structured KPI architecture across service, resource, and environmental dimensions. After mapping loss

hot-spots through Green Value Stream Mapping (Green VSM) and aligning emissions accounting with ISO 14083/GLEC, two analytical cores run in parallel: baseline benchmarking (e.g., DEA) to diagnose inefficiencies and scenario-based multi-objective optimisation (including PRP-type routing) to generate improvement options. The final output is an implementation-ready package that combines Pareto trade-offs with quantified targets and a practical roadmap. Accordingly, this section is structured to answer three practical questions in a directly implementable way:

1. Within what process boundaries should the optimisation problem be formulated?
2. With what performance-metric architecture should process performance be measured and monitored?
3. How should improvement combine the logic of “best plan” (optimisation) with “relative effectiveness” (efficiency analysis)?



**Figure 1.** *Integrated framework for green logistics process optimisation and efficiency analysis*

The integrated framework proposed here is designed to prevent a common failure mode in sustainability initiatives: strong intentions and dashboards, but weak decision logic—where teams measure many indicators yet cannot translate them into robust, prioritised, and model-supported interventions.

**2.1. Process boundaries and decision levels: drawing the “from-to” line correctly**

The most critical first step in process optimisation and efficiency analysis is to avoid leaving “the logistics process” as an abstract concept. If system boundaries are not explicit, different teams inside the same organisation may count energy, emissions, or service outcomes under different scopes. When this happens, optimisation outputs and benchmarking results become non-comparable and often contested. For this reason, the process boundary should be defined explicitly across three decision levels:

- Network level (strategic design). This includes depot/terminal locations, the number of facilities, region assignment, mode choice (road–rail–sea–intermodal), and capacity decisions. Environmental performance at this level is largely structural: the physical footprint of the network, average transport distances, modal mix, and terminal proximity often determine the feasible emissions baseline. OR research emphasises that design decisions frequently dominate long-term cost and emissions and can amplify the value of later operational improvements (Dekker, Bloemhof, & Mallidis, 2012).

- Planning level (tactical planning). This covers shipment consolidation rules, routing and time-window planning, fleet composition (conventional/alternative fuels/EV), and inventory–transport coordination. At this level,

environmental impact becomes rule-driven: consolidation frequency, fill rates, routing policies, and time-window rigidity directly shape vehicle-kilometres, empty running, and stop density.

- Execution level (operational control). This includes loading plans, speed profiles, idling, driving behaviour, warehouse picking/handling routes, energy management (HVAC/lighting), and real-time replanning. Environmental performance here is behavioural and control-sensitive, meaning variance, disruptions, and operational discipline materially affect outcomes.

A key conceptual point in green logistics is that the “environmental dimension” enters the decision system differently at each level: structural choices at network design, policy choices at planning, and real-time control choices at execution. This classification is not just descriptive; it is a model-building guide: it tells the analyst which decision variables and constraints are meaningful and what types of data must be collected.

## **2.2. Measurement architecture: moving beyond a single KPI to a performance system**

Green logistics process optimisation is inherently multi-objective: firms must protect (or improve) cost and service performance while reducing emissions and energy intensity. Therefore, performance measurement should not rely on one headline KPI; it must be designed as a metric architecture that supports decision-making. In practice, three metric families should be tracked together:

- Service metrics (customer-facing outcomes). Examples include on-time delivery rate, delivery lead time, time-window compliance, damage/returns rates, and service reliability.

- Resource metrics (input and utilisation indicators). Examples include vehicle-kilometres, fill rate, empty-kilometre ratio, driver hours, warehouse labour hours, equipment utilisation, and warehouse energy consumption.

- Environmental metrics (impact indicators). Examples include CO<sub>2</sub>e per ton-kilometre, CO<sub>2</sub>e per shipment, energy intensity (kWh per unit handled, kWh per m<sup>2</sup>), and packaging material per parcel.

The crucial methodological requirement is that environmental metrics must be computed using a standardised and auditable method. ISO 14083:2023 provides a consistent methodology for quantifying and reporting GHG emissions arising from transport chain operations, helping ensure comparability across scenarios and organisational units (ISO, 2023). This matters for two reasons:

1. Model integrity. If the emissions component in the objective function is computed inconsistently, “optimal” results can become artefacts of accounting choices rather than real operational improvements.

2. Organisational acceptability. Even an analytically optimal plan can fail in implementation if it cannot be defended under internal governance or external reporting/assurance expectations.

A practical recommendation follows directly: emission factors and the environmental variables used in efficiency analysis should be defined in a way that is consistent with the selected emissions-accounting standard (e.g., ISO 14083 or an equivalent corporate framework), otherwise results may be rejected at the reporting and audit stages.

### **2.3. Process discovery and making improvement opportunities visible: VSM-based sustainability mapping**

A frequent practical mistake in process optimisation is that the mathematical model is built “correctly” yet improvement efforts target the wrong place—because the real losses in the physical process (waiting, unnecessary motion, weak consolidation, low fill rates, re-handling in warehouses, idling) were not located systematically. For this reason, green logistics initiatives benefit from an explicit process discovery step before modelling. Value Stream Mapping (VSM), when extended with sustainability variables (“green VSM” or environmental VSM), offers two direct advantages:

- A single map for multiple flows. Material flow, information flow, and key energy/emissions points can be represented together. This makes it easier to see where service promises, batch sizes, and dispatch rules create hidden environmental costs.

- Localising losses in the process. Instead of treating emissions as a global number, the analyst can ask process-level questions: *Where does energy intensity spike? Where does idling or re-handling occur? Which step drives the most avoidable kilometres?*

Green VSM extensions proposed in the literature aim to link operational waste reduction and environmental improvement in the same diagnostic layer, particularly highlighting the warehouse–distribution interaction where local efficiency can generate system-level emissions penalties if not coordinated (Muñoz-Villamizar et al., 2019). A key principle should be emphasised in a book-chapter context: VSM does not replace optimisation; it makes optimisation more correct by defining the right boundary, the right decision points, and the right data requirements. In other words, the process map helps answer “what to model,” and optimisation then answers “what to do.”

#### **2.4. The optimisation core: decision models that balance emissions, cost, and service**

In many real logistics contexts, the strongest and fastest-acting improvement lever is transport planning—routing, scheduling, consolidation, and operating policies—because small planning changes can directly alter vehicle-kilometres, fill rates, and therefore emissions. However, representing environmental impact correctly often requires moving beyond “distance minimisation.” When emissions depend on speed and load, routing must be combined with driving/operating profiles. The Pollution-Routing Problem (PRP) introduced by Bektaş and Laporte formalises this requirement: the objective function incorporates fuel and emissions components, and speed decisions can become part of the model rather than a fixed assumption (Bektaş & Laporte, 2011). The practical insight is important: the lowest-distance route may not be the lowest-emissions route when speed, congestion, stop patterns, and load dynamics are considered. Within the scope of this chapter, optimisation should be understood not as “one model,” but as a layered family of models aligned with decision levels:

- Routing and consolidation optimisation: reducing trips, improving fill rates, redesigning time-window policies, and assessing consolidation scenarios.
- Warehouse process optimisation: picking paths, slotting/layout decisions, equipment use, and energy management (especially HVAC and lighting loads).
- Network-level scenarios: facility count/location, cross-docking, and modal shift/intermodal redesign.

Across these layers, the deliverable is rarely “a single best number.” Instead, decision-makers need a transparent trade-off surface—cost ↔ service ↔ emissions—so that operational feasibility and stakeholder priorities can be explicitly managed.

#### **2.5. The efficiency-analysis core: relative efficiency, environmental outputs, and improvement targets**

While optimisation searches for the best plan under a model, efficiency analysis—especially DEA-type approaches—answers a different but complementary question: how effective is the current operation relative to peers or comparable units? Typical benchmarking questions in green logistics include:

- Which warehouses deliver comparable throughput and service with lower energy use?
- Which routes/regions achieve lower emissions intensity for similar service constraints?

- Which fleet segments convert kilometres, hours, and fuel into delivery outputs more efficiently?

DEA has a strong tradition in energy and environmental applications because it can handle multiple inputs and outputs without collapsing them into a single monetary metric (Zhou, Ang, & Poh, 2008). In logistics, environmental performance can be incorporated either by treating emissions as an undesirable output or by embedding environmental indicators directly into the output set, enabling “operational + environmental” efficiency to be evaluated jointly. Applied studies have used DEA variants to incorporate environmental impacts into transport efficiency assessment, illustrating how benchmarking changes when emissions are included as part of the performance definition (Tang, You, Sun, & Zhang, 2019).

For this book chapter, the key contribution of efficiency analysis is managerial as much as analytical:

- Optimisation helps decide what to do next (best plans under scenarios).

- Efficiency analysis clarifies where we are now and where the potential is largest (diagnosis and target setting).

Because DEA can produce target values (how much input to reduce or output to increase to reach the efficient frontier), it supports implementation by converting “improvement ambition” into measurable process goals.

## **2.6. Integrating optimisation and efficiency analysis: an implementation-ready roadmap**

An integrated roadmap that works well in practice can be expressed as a sequence of steps:

- Process discovery and data dictionary. Use VSM or similar mapping to define the process boundary, identify measurement points, and specify what data is required and where it resides.

- Standards-aligned emissions accounting. Align emissions computation and reporting definitions with the chosen standard (e.g., ISO 14083), ensuring the optimisation model and performance reporting speak the same language (ISO, 2023).

- Baseline efficiency screening. Run benchmarking (e.g., DEA) at the relevant decision-unit level (warehouse/route/region/fleet segment) to identify where improvement potential is concentrated.

- Scenario-based optimisation. For high-potential areas, run multi-objective optimisation to generate implementable options—routing/consolidation changes, time-window redesign, warehouse energy rules—

and, where relevant, PRP-type structures to represent speed/load-dependent emissions (Bektaş & Laporte, 2011).

- Decision-maker packaging. Present outputs as a choice set: Pareto options + benchmark targets + operational roadmap, structured explicitly around cost–service–emissions trade-offs.

This roadmap converts green logistics improvement from a set of isolated initiatives into a measurable loop: map → standardise → benchmark → optimise → implement → monitor, supporting continuous improvement rather than one-off projects.

### 3. Modelling and Implementation Design

This section explains how to transform green-logistics process optimisation and efficiency analysis from a one-off report into an institutionalised decision-support pipeline that can be repeated, audited, and operationalised. The guiding logic is straightforward:

1. Standardise data and emissions accounting,
2. Use optimisation to generate the best plan / scenario set,
3. Use efficiency analysis to quantify which depot/route/fleet is relatively effective and where the improvement potential is,
4. Integrate both outputs into an implementable improvement package.

The design explicitly aims to minimise two common field risks: (i) scenarios cannot be compared because emissions are calculated inconsistently, and (ii) optimisation looks strong “on paper” but fails to address the organisation’s real inefficiency hot-spots. These risks are well-known in the green-logistics OR literature, where decision quality depends heavily on boundary definition and on embedding the environmental dimension into design–planning–control decisions (Dekker, Bloemhof, & Mallidis, 2012).

#### 3.1. System boundary, process map, and decision unit definition

Before modelling starts, the most important task is to answer: “Which process are we optimising, and which entities are we benchmarking?” In green logistics, even within the same firm, energy and emissions can be reported under different scopes—undermining both optimisation validity and benchmarking credibility. For implementation purposes, define the application unit at two levels:

(1) Process boundary (“from–to”). At minimum, specify the operational start and end points for each process family:

- Transport/distribution boundary: depot dispatch → customer points → return (or next hub/terminal).

- Warehousing/handling boundary: receiving → put-away → picking → packing → shipping.

This “from-to” definition must be consistent with how emissions are quantified for the transport chain, because optimisation results can only be compared if the accounting boundary is stable and auditable (ISO, 2023).

(2) Decision-making unit (DMU) for efficiency analysis. Select the unit to be compared in DEA-style benchmarking. Three practical options dominate:

- DMU = Warehouse / distribution centre: strong measurability for energy, labour, throughput, and service quality.

- DMU = Route / lane / region: strong observability for vehicle-km, fuel, stop density, on-time performance, and emissions intensity.

- DMU = Fleet segment: urban delivery vs. line-haul vs. intermodal, allowing segment-level comparisons.

Practical rule: choose the DMU where the data are strongest and most stable. If route telemetry is reliable, benchmarking lanes is often more defensible; if warehouse metering is mature, a DC-based DMU is more robust.

### 3.2. Data architecture and ISO 14083-aligned emissions accounting

In green logistics, what we call “optimal” is often highly sensitive to how emissions are calculated. Therefore, emissions accounting should not be appended as an afterthought; it must be treated as a core input layer. ISO 14083:2023 establishes a common methodology for quantification and reporting of GHG emissions arising from transport chain operations, directly supporting comparability and auditability (ISO, 2023). The goal in practice is to guarantee two things:

- Scenario comparability: all scenarios are evaluated in the same accounting language.

- Audit clarity: when challenged, the organisation can answer: “How exactly was this CO<sub>2</sub>e calculated?”

Minimum viable dataset (field-ready baseline).

Operational data (transport): customer points, quantities (kg/ton/collis), time windows, distance/time matrix (or digital routes), vehicle capacities, trip counts, utilisation/fill-rate proxies.

Energy/fuel data: fuel type, consumption (L/100km or kWh/km), idling time, and—if available—speed/stop patterns (especially for urban contexts).

Environmental parameters: CO<sub>2</sub>e emission factors consistent with the chosen boundary and method (e.g., TTW/WTW definitions as adopted in the organisation’s framework).

Warehouse data (if included): metered kWh (monthly/weekly), floor area (m<sup>2</sup>), equipment hours, order lines / throughput, picking distances or step counts.

Why this matters: environmental optimisation is rarely “distance minimisation.” If emissions coefficients are inconsistent, the model may end up optimising the wrong driver—producing results that do not survive operational scrutiny or reporting requirements (ISO, 2023).

### **3.3. Building the optimisation model: decision variables, objectives, and constraints**

For a aimed at implementation, the optimisation model should not be presented as an abstract block of equations; it should be built as a representation of field decisions, such as:

- How should shipments be consolidated?
- How should routes and timing be scheduled?
- How can utilisation and fill rates be increased?
- How can emissions be reduced without harming service level?
- If warehousing is included: how can internal handling and energy use be improved?

Core decision variables (transport example). Typical variables include assignment (which vehicle serves which customers), sequencing (visit order), timing (arrival times under time windows), and potentially operational policy variables such as consolidation choices. In advanced formulations, driving profile variables can be introduced when justified by data availability.

Objective design. Because green logistics is multi-objective, two implementable approaches are common:

- Weighted-sum objective: cost + emissions + delay/penalty integrated into a single function (useful for operational rollout).
- Multi-objective (Pareto) optimisation: produces a set of alternatives revealing explicit trade-offs between cost, emissions, and service (useful for strategic decision-making and stakeholder alignment).

Minimum constraint set (field realism).

- Demand fulfilment and route continuity,
- Vehicle capacity,
- Time windows,
- Driver/vehicle working time,

- Depot start/end (or connection to next hub).

Constraints that strengthen the “green” dimension (high-impact in practice).

- Emissions budget cap (total CO<sub>2</sub>e ≤ threshold),
- Minimum utilisation / fill-rate constraints,
- Maximum empty-kilometre share,
- EV constraints (range/charging), where applicable.

A crucial point for credibility is embedding emissions/energy into the decision model, not merely reporting it afterward. This is particularly important when emissions depend on speed and load. The Pollution-Routing Problem (PRP) formalises this by incorporating fuel/emissions and travel-time costs into routing decisions, highlighting that “shortest distance” is not necessarily “lowest emissions” when load and speed matter (Bektaş & Laporte, 2011).

Solution approach (implementation-oriented).

- Use a small instance to obtain a reference optimum via MILP.
- For real-scale instances, deploy heuristics/metaheuristics for operationally feasible solutions.
- If multi-objective, communicate results as a Pareto set rather than a single number.

### **3.4. Efficiency analysis (DEA): where are we lagging and how much can we improve?**

Optimisation answers: “What plan would be best under model assumptions?” Efficiency analysis answers: “How effective is the current operation relative to peers, and where is the potential largest?”

DEA is particularly suitable in green logistics because processes typically have multiple inputs (energy, vehicle-km, labour, fleet hours) and multiple outputs (throughput, deliveries, service level). In energy and environmental applications, DEA has been widely reviewed as a flexible benchmarking tool precisely because it can incorporate multiple dimensions without forcing everything into a single monetary unit (Zhou, Ang, & Poh, 2008).

The key green-logistics challenge: CO<sub>2</sub>e is an undesirable output. In standard DEA, “more output is better,” but emissions should be reduced. Two practical treatments are common:

- Option 1 — treat CO<sub>2</sub>e as an input (simpler field implementation). This treats emissions as a resource to be minimised. It is pragmatic and often

sufficient for managerial rollout when the goal is clear benchmarking and target-setting.

- Option 2 — model undesirable outputs explicitly (diagnostic depth). Approaches include Slack-Based Measure (SBM) models and transformations that preserve linearity while allowing desirable outputs to increase and undesirable outputs to decrease. The SBM framework is a widely used DEA extension focusing directly on input excesses and output shortfalls (Tone, 2001).

For undesirable outputs specifically, a classic treatment demonstrates how to handle undesirable factors while preserving convexity/linearity (Seiford & Zhu, 2002). Directional distance functions provide another foundation for jointly expanding good outputs and contracting bad outputs (Chung, Färe, & Grosskopf, 1997).

Variable selection principle (avoid “too many variables”). The objective is not to include everything; it is to include variables that represent process decisions and are comparable across DMUs.

Examples:

- DMU = Warehouse

Inputs: energy (kWh), labour hours, equipment hours. Outputs: throughput (order lines/shipments), on-time dispatch rate. Environmental: CO<sub>2</sub>e (energy-related; plus allocated transport share if needed)

- DMU = Route/Lane

Inputs: vehicle-km, driving hours, fuel consumed. Outputs: number of deliveries, tons delivered, service-level indicator. Environmental: CO<sub>2</sub>e

Managerial value of DEA: it not only labels units as efficient/inefficient but can also generate improvement targets (e.g., “reduce energy by X% or increase throughput by Y%”)—making improvement operationally actionable.

### **3.5. Integrating optimisation and DEA: two field-proven patterns**

The most practically valuable contribution of this chapter is to combine both approaches into an implementation logic. Two integration patterns are especially useful:

(A) DEA first, optimisation second (targeting-oriented).

1. Run DEA on the current system to identify underperforming depots/routes/fleet segments.
2. Extract improvement targets (slacks/benchmarks).
3. Use optimisation to design a process plan that can achieve these

targets (consolidation rules, routing, time-window design, warehouse operating policies).

This approach directs scarce improvement resources to the largest potential first.

(B) Optimisation first, DEA second (scenario-selection-oriented).

1. Generate scenario options via optimisation: cost-min, emissions-min, balanced Pareto options.

2. Compute DMU-level KPIs under each scenario.

3. Apply DEA to compare scenarios by “efficiency + greenness,” helping select the most implementable option from the Pareto set.

This approach is powerful when the organisation already has alternative strategies on the table and needs a defensible selection mechanism.

### **3.6. Reporting and decision-maker packaging: Pareto set + targets + implementation plan**

The output of the modelling pipeline should not be “tables only.” Decision-makers need a package that answers “Why this option?” and “What exactly changes in operations?” A robust reporting package typically includes:

- Optimisation output: Pareto solutions (cost–emissions–service), chosen scenario, and operational policies implied by the solution.

- DEA output: DMU efficiency scores and target values (what to reduce, what to improve).

- Integrated narrative:

- o “This depot has high energy intensity; this lane generates empty kilometres.”

- o “These two interventions reduce CO<sub>2</sub>e by X while keeping service within Y.”

- o “Implementation requirements: data feeds, process rules, monitoring cadence.”

This packaging makes the pipeline repeatable and defensible—supporting institutional adoption rather than one-time reporting.

## **4. Application Scenario and Sample Data Structure**

The purpose of this section is not to provide a generic narrative, but to construct a concrete, numerical, and fully explained example that readers can directly replicate using their own organisational data. For that reason, the section provides:

- a small-scale but realistic distribution problem,
- the complete dataset in table form,
- a comparison between a baseline (current) plan and an improved (greener) plan,
- results reported not only as totals, but also as vehicle-level routes and time schedules.

The scale of the example (6 customers, 2 vehicles) is intentionally small so that the reader can see the full chain—data → calculation → outputs—in one pass. In practice, the same workflow is applied to large instances (100+ customers) using optimisation software.

#### 4.1. Problem definition and scenario context

Scenario. A single distribution depot (D0) performs daily deliveries. Some customers impose time windows, and each stop requires a fixed service time. Two vehicles must visit all customers, and each route starts and ends at the depot. In this setting, “green logistics” is treated as the outcome of planning decisions, not a slogan: same service with less distance → less fuel → less CO<sub>2</sub>e. The decision problem can be reduced to four questions:

1. Which customers are assigned to which vehicle?
2. In what sequence does each vehicle visit its customers?
3. How is time-window feasibility maintained?
4. How do km, fuel, CO<sub>2</sub>e, and cost change as a result?

#### 4.2. Assumptions and parameters

To keep the example transparent, parameters are chosen as single values (in real operations, they often vary by vehicle type, traffic, season, and load),

**Table 1.** Scenario Assumptions and Parameters

Parameter	Value	Explanation
Number of vehicles	2	Daily distribution
Vehicle capacity	1,000 kg	Per vehicle
Average speed	40 km/h	Simplified constant speed
Fuel consumption	0.25 L/km	Fixed rate (simplified)
Emission factor	2.68 kgCO <sub>2</sub> e/L	Example diesel factor
Variable cost	12 TL/km	Distance-based operating cost
Fixed cost	200 TL/vehicle-day	Dispatch/availability cost
Service time	10 min/stop	At each customer

Implementation note. In a real deployment, these coefficients should be updated from the company’s telematics/consumption records and aligned

with the selected emissions-accounting boundary and reporting logic (e.g., ISO 14083) to maintain scenario comparability and auditability (ISO, 2023).

**4.3. Sample dataset (customer table)**

Coordinates (x, y) represent a simplified map. Demand, time windows, and service times are the core inputs for routing and scheduling.

**Table 2.** *Customer Dataset*

Stop	x	y	Demand (kg)	Time window	Service (min)
D0 (Depot)	0.0	0.0	–	–	–
C1	2.0	1.0	180	09:00–12:00	10
C2	3.0	0.5	220	09:00–12:00	10
C3	4.0	1.5	260	10:00–14:00	10
C4	-1.5	2.5	200	09:30–13:00	10
C5	-2.5	1.0	240	09:30–13:00	10
C6	-3.0	3.0	280	10:00–15:00	10

Distance calculation (illustrative). For this example, distances are computed using Euclidean distance:

$$d(i, j) = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

In real applications, Euclidean distances should be replaced with a road-network distance–time matrix from GIS or routing services to reflect actual travel conditions.

**4.4. Calculation workflow: from data to results**

For each route, we compute the following:

1. Route distance (km).

Start at D0 → visit assigned customers in sequence → return to D0; sum leg distances.

2. Fuel consumption (L).

$$\text{Fuel} = \text{Distance} \times 0.25$$

3. CO<sub>2e</sub> emissions (kg).

$$\text{CO}_{2e} = \text{Fuel} \times 2.68$$

4. Cost (TL).

$$\text{Cost} = (\text{Fixed cost per vehicle}) + (\text{Distance} \times 12)$$

Fixed cost is incurred if the vehicle is dispatched; here, both vehicles are used, so fixed cost is counted twice.

5. Time schedule (time-window feasibility).
  - Travel time = Distance / Speed
  - If arrival is earlier than the time window start, waiting occurs
  - If arrival is later than the time window end, lateness is recorded
  - Service time (10 minutes) is added at each stop

A key methodological message: whether implemented in Excel, code, or a TMS, the same logic applies.

#### 4.5. “Current plan” (Baseline) – route results

This plan is typical in practice: customers are sensibly clustered (east vs. west), but the visit order is not optimised.

**Table 3.** *Baseline Plan – Route Results by Vehicle*

Vehicle	Route	Load (kg)	Distance (km)	Fuel (L)	CO <sub>2</sub> e (kg)	Cost (TL)
V1	D0–C1–C2–C3–D0	660	9.040	2.260	6.057	308.484
V2	D0–C4–C5–C6–D0	720	11.022	2.756	7.385	332.269
Total		1380	20.063	5.016	13.442	640.753

Commentary (book-chapter style). Capacity feasibility is satisfied (both routes remain below 1,000 kg). However, the key “green” weakness remains: avoidable kilometres persist. In many organisations this is normalised as “how we operate,” yet at annual scale it translates into substantial fuel and emissions burdens.

#### 4.6. “Improved plan” (Green scenario) – route results

Now we keep the same customer grouping but improve only the visit sequence (often the easiest operational improvement to implement). The result is:

**Table 4.** *Improved (Green) Plan – Route Results by Vehicle*

Vehicle	Route	Load (kg)	Distance (km)	Fuel (L)	CO <sub>2</sub> e (kg)	Cost (TL)
V1	D0–C1–C3–C2–D0	660	8.753	2.188	5.865	305.039
V2	D0–C4–C6–C5–D0	720	9.251	2.313	6.198	311.009
Total		1380	18.004	4.501	12.063	616.048

Commentary. This is not a “major transformation”: fleet size, depot location, and customer set are unchanged. Only sequencing is improved—yet total distance drops, and that reduction propagates directly to fuel and CO<sub>2</sub>e.

This reinforces a central message of the chapter: green performance gains frequently emerge as a natural by-product of process optimisation (Bektaş & Laporte, 2011).

**4.7. Summary comparison and decision-relevant gains**

This table provides the most decision-relevant summary for managers:

**Table 5.** *Summary Comparison of Baseline vs. Improved Plan*

Metric	Baseline	Improved (Green)	Difference	Difference %
Total distance (km)	20.063	18.004	-2.059	-10.26%
Total fuel (L)	5.016	4.501	-0.515	-10.26%
Total CO <sub>2</sub> e (kg)	13.442	12.063	-1.379	-10.26%
Total cost (TL)	640.753	616.048	-24.706	-3.86%

Interpretation.

- The CO<sub>2</sub>e reduction mirrors fuel reduction because the emission factor is held constant.

- The cost reduction is smaller because part of cost is fixed (200 TL per vehicle). This is a valuable managerial insight: when fixed dispatch costs are significant, “green” improvements can reduce emissions quickly while producing a more modest change in total cost.

**4.8. Time schedule (timetable): demonstrating time-window feasibility**

To ensure the improvement is not merely “on paper,” we explicitly answer the operational question: Do routes respect time windows? Is there waiting or lateness?

**Table 6.** *Vehicle V1 Timetable under the Improved (Green) Plan*

Stop	Leg (km)	Arrival	Waiting (min)	Lateness (min)	Departure/Return	Demand (kg)
C1	2.236	09:03	0	0	09:13	180
C3	2.062	10:00	43	0	10:10	260
C2	1.414	10:12	0	0	10:22	220
Return D0	3.041	–	–	–	10:26	–

Commentary. The critical observation is the 43-minute waiting at C3. This is not necessarily “bad”—it may be a natural consequence of time windows. However, it signals a clear improvement lever for subsequent sections: if the organisation wants to reduce waiting, it must either (i) renegotiate/relax time windows or (ii) redesign customer-to-vehicle assignment and route structure.

**Table 7.** *Vehicle V2 Timetable under the Improved (Green) Plan*

Stop	Leg (km)	Arrival	Waiting (min)	Lateness (min)	Departure/Return	Demand (kg)
C4	2.915	09:30	25	0	09:40	200
C6	1.581	10:00	17	0	10:10	280
C5	2.062	10:13	0	0	10:23	240
Return D0	2.693	–	–	–	10:27	–

Commentary. This vehicle also experiences waiting but no lateness, indicating that the “greener” plan remains operationally feasible and service-compliant. In a book chapter, this timetable evidence is important because it demonstrates that optimisation can reduce kilometres without sacrificing service commitments.

## 5. Conclusion

This chapter argued that improving sustainability in logistics is less about adding isolated “green practices” and more about redesigning the decision logic of logistics processes so that cost, service, and environmental performance are managed jointly. Under climate and regulatory pressure, logistics decisions increasingly shape a firm’s value-chain emissions and operational resilience; therefore, environmental performance must be embedded into the same planning and control mechanisms that already govern service quality and cost. A central contribution of the chapter is the integrated view that process optimisation and efficiency analysis are complements, not substitutes. Optimisation supports the question, “What is the best plan (or best set of trade-off plans) under our operational constraints?” while efficiency analysis addresses, “Where are we underperforming relative to comparable units, and what is the improvement potential?” When combined, these approaches create an implementation-ready improvement loop: define boundaries and DMUs → design KPI architecture → standardise emissions accounting → benchmark (DEA) → optimise scenarios → package targets and actions. This integration is strongly aligned with the OR perspective that green logistics must be treated across design–planning–control layers, rather than as a single operational adjustment (Dekker et al., 2012; Sbihi & Eglese, 2010).

The chapter also emphasised that measurement is not a reporting afterthought: it is a modelling prerequisite. Scenario results are only credible and comparable if emissions are calculated with a consistent boundary and method. ISO 14083 provides a practical foundation for quantifying and reporting GHG emissions from transport chain operations, supporting auditability and comparability across scenarios and organisational units (ISO, 2023). Without such standardisation, “optimal” solutions risk reflecting accounting differences rather than genuine operational gains. The numerical

application scenario (6 customers, 2 vehicles) illustrated an important operational reality: meaningful emissions reductions can emerge from low-disruption process improvements. In the example, improving only the visit sequence reduced total distance, fuel use, and CO<sub>2</sub>e, while maintaining time-window feasibility. Although simplified, the example demonstrates the mechanism through which many green gains materialise—by reducing avoidable kilometres, improving utilisation, and controlling waiting/idle patterns—rather than solely relying on technology substitution. This logic is consistent with routing models that explicitly incorporate fuel/emissions considerations, such as the Pollution-Routing Problem, which shows why shortest distance is not always lowest emissions when operational factors interact.

From a managerial standpoint, three practical implications follow:

1. Govern the problem boundary before governing solutions. Without stable process boundaries and DMU definitions, debates about results tend to become debates about scope.

2. Treat KPIs as a decision system, not a dashboard. A structured KPI architecture across service, resource, and environmental metrics allows process changes to be evaluated consistently and prevents “local” improvements from creating “system-level” penalties.

3. Translate analytics into implementable targets. DEA-style benchmarking is valuable not only for scoring performance but also for converting improvement ambition into measurable targets (e.g., reduce energy intensity, reduce empty kilometres), which increases organisational adoption (Zhou et al., 2008; Tone, 2001; Seiford & Zhu, 2002).

At the same time, the chapter acknowledges limitations that readers should consider when applying the framework. The application scenario uses simplified distances and constant speed and fuel rates; real systems require road-network travel times, stochastic demand, traffic variability, and vehicle heterogeneity. Emissions modelling can also become more complex under well-to-wheel boundaries, alternative fuels, and electrified fleets, and warehouse energy impacts often vary seasonally and operationally. These realities do not reduce the value of the framework; rather, they underline the importance of robust data governance and iterative refinement.

Future work and extensions are therefore clear. Methodologically, combining multi-objective optimisation with richer uncertainty modelling (e.g., stochastic or robust formulations) can improve reliability under real variability. In efficiency analysis, undesirable-output DEA variants and dynamic benchmarking can better capture environmental performance while accounting for operational heterogeneity and time trends. Practically,

organisations can extend the framework from routing and warehousing toward network redesign, modal shift evaluation, and integrated forward–reverse flow coordination, where multi-objective trade-offs become even more central.

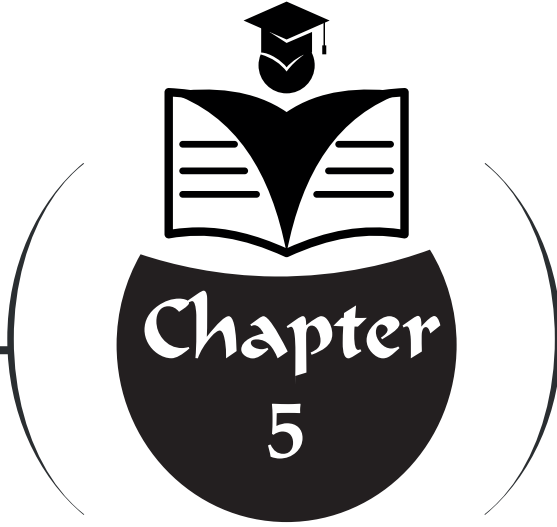
In conclusion, green logistics performance improves most reliably when sustainability is treated as a process optimisation and governance problem: measured consistently, benchmarked fairly, optimised transparently, and implemented through concrete operating rules and targets. By integrating optimisation with efficiency analysis under standardised emissions accounting, the chapter provides a replicable pathway for organisations to achieve measurable, defensible, and operationally feasible reductions in emissions and resource intensity while maintaining service commitments.

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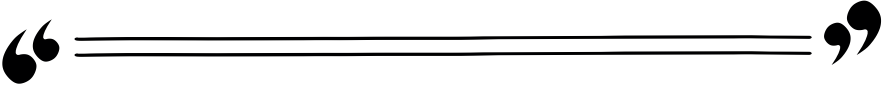
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**GREEN LOGISTICS WITH ARTIFICIAL  
INTELLIGENCE, OPTIMIZATION, AND SMART  
SYSTEMS**



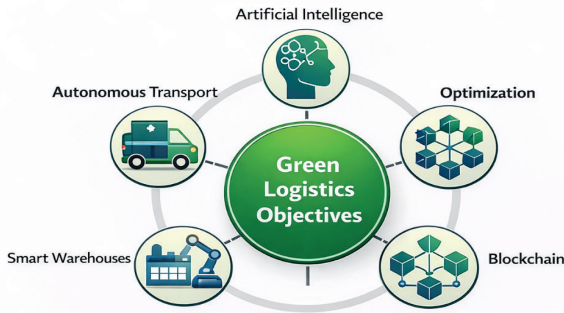
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Today, logistics systems are undergoing a significant transformation due to increasing environmental pressures, global competition, and the impact of digitalization. In this transformation, artificial intelligence, optimization methods, and smart systems stand out as key technologies that both increase the operational efficiency of logistics activities and support environmental sustainability goals. The green logistics approach aims to reduce the environmental impact of logistics processes through the integrated use of these technologies. In this context, artificial intelligence technologies are becoming one of the main driving forces of the green logistics transformation by offering capabilities such as data-driven decision-making, predictive analysis, dynamic optimization, and autonomous operations management. Logistics systems are no longer managed solely based on cost and service level; they are also managed in accordance with environmental performance indicators such as energy consumption, carbon emissions, and resource efficiency.

This section first addresses the conceptual foundations of artificial intelligence technologies in the context of green logistics, and then examines multi-objective optimization problems that address conflicting goals such as cost, energy consumption, and carbon emissions, as well as AI-based solution approaches for these problems. Furthermore, the contribution of blockchain technology to verifying transparency, traceability, and sustainability performance in supply chains is evaluated; and real-world applications of artificial intelligence through smart warehouses and autonomous logistics systems are analyzed. Finally, a comprehensive assessment is presented by discussing trends, open research areas, and technical and ethical challenges for the future of AI-powered systems in green logistics.



*Figure 1. AI-based digital ecosystem structure in green logistics*

In this multi-layered digital transformation process, the integration of artificial intelligence, optimization, blockchain, and smart logistics technologies creates a critical digital ecosystem structure for establishing sustainable logistics systems. The conceptual structure of this ecosystem is shown in Figure 1.

## 1. The Role of Artificial Intelligence in Green Logistics

Logistics systems are becoming increasingly complex and dynamic with the growing global trade volume, urbanization, the spread of e-commerce, and the diversification of customer expectations. These developments significantly increase the environmental impacts of logistics activities, such as energy consumption, carbon emissions, and the use of natural resources. In this context, green logistics stands out as a holistic approach that aims to reduce the environmental impacts of logistics processes and align them with sustainable development goals. In this transformation process, artificial intelligence (AI) plays a central role not only as a technology that provides operational automation, but also as a strategic tool that enables data-driven, adaptive, and multi-objective decision-making processes (Toorajipour et al., 2021; Helo & Hao, 2022; Culot et al., 2024).

While traditional logistics systems are mostly based on static rules, past experiences, and limited data usage, AI-powered systems can learn from real-time data, generate future predictions, and directly integrate environmental impacts into decision-making mechanisms. In this respect, AI creates a “decision intelligence” layer in green logistics that simultaneously performs the functions of measuring, predicting, and optimizing (Ivanov & Dolgui, 2020).

### 1.1. Artificial Intelligence Approaches: The Role of ML, DL, RL, and Optimization

In logistics applications, artificial intelligence is generally addressed under four main approaches, depending on the nature of the decision problems and the data structure: Machine Learning (ML), Deep Learning (DL), Reinforcement Learning (RL), and AI models integrated with optimization. These approaches play complementary roles at different decision levels in line with green logistics goals. The deployment of artificial intelligence techniques used at strategic, tactical, and operational decision-making levels is shown in Figure 2.



*Figure 2. Positioning artificial intelligence approaches according to logistical decision levels*

**Machine learning** forms the basis of predictive analytics in logistics systems. Problems such as demand forecasting, delivery time estimation, maintenance requirement prediction, and capacity planning are prime areas where ML techniques excel. These applications can reduce unnecessary trips, decrease inventory surpluses, and improve equipment utilization efficiency. Therefore, ML-based approaches have the potential to indirectly but systematically reduce energy consumption and carbon emissions in logistics operations. Extensive systematic reviews of the supply chain literature clearly demonstrate the contributions of artificial intelligence techniques in different subfields and which methods are more effective for which types of problems (Toorajipour et al., 2021).

**Deep learning** stands out in logistics environments with high-dimensional and heterogeneous datasets. Monitoring in-warehouse operations through image and video analytics, combining vehicle telematics and environmental data via sensor fusion, and automatically learning complex patterns are typical application areas of DL. This makes operational waste in warehousing and transportation activities more visible, creating new opportunities for process improvement and energy efficiency. Current systematic literature reviews focusing on empirical studies discuss in detail the impact of RL-based approaches on real-world deployment conditions and sustainability performance (Choi et al., 2018; Culot et al., 2024).

**Reinforcement learning** offers a powerful framework for time-varying and uncertain logistics decision problems. In scenarios such as route updating, fleet routing, dynamic pricing, and capacity management, RL enables an agent to learn the optimal decision policy through trial and error by interacting with its environment. The importance of RL in the context of green logistics is increasing, especially in intra-city distribution systems with high traffic density and demand fluctuations. This approach allows for the simultaneous optimization of total cost as well as environmental goals such as energy consumption and emissions (Baryannis et al., 2019).

However, a large proportion of green logistics problems have a multi-objective decision-making structure, and therefore artificial intelligence is often addressed in conjunction with optimization methods. The simultaneous consideration of potentially conflicting objectives such as cost, time, and carbon emissions makes AI-assisted optimization models inevitable. Recent reviews of the green vehicle routing problem literature show that multi-objective meta-heuristic methods (e.g., NSGA-II) have become the dominant approaches in this field (Garside et al., 2024). This demonstrates that in green logistics, artificial intelligence is positioned not only as a predictive tool but also as an optimization-based decision support mechanism.

## **1.2. Automation and Intelligence in Logistics Processes**

Unlike traditional automation approaches, AI-powered logistics systems offer a structure that can learn, adapt, and make autonomous decisions. In processes such as route planning, load consolidation, warehouse management, inventory control, and maintenance planning, AI-based automation minimizes operational errors by reducing human intervention. More importantly, these systems can directly integrate environmental indicators such as energy consumption and emissions into decision-making mechanisms (Helo & Hao, 2021).

Intelligent decision support systems combine AI algorithms with mathematical optimization models, offering logistics managers the opportunity to balance cost, time, and environmental impact. This approach is critical for the multi-objective decision-making requirement that forms the basis of green logistics. Thus, logistics processes can be systematically evaluated not only according to economic performance criteria but also in line with sustainability goals (Toorajipour et al., 2021).

## **1.3. Artificial Intelligence from an Environmental Sustainability Perspective**

One of the most important contributions of artificial intelligence to green logistics is making environmental impacts measurable and manageable. Indicators such as energy consumption, carbon emissions, vehicle occupancy rate, and idle mileage can be continuously monitored and analyzed thanks to AI-based systems. This ensures that environmental performance becomes an integral part of operational decisions.

AI-supported prediction and optimization approaches contribute to reducing the environmental footprint by decreasing resource waste in logistics activities. However, the literature emphasizes that the environmental benefits of artificial intelligence do not emerge automatically; data quality, algorithm selection, system integration, and governance structures are decisive in realizing these benefits (Baryannis et al. 2019; Culot et al., 2024). Therefore, the effective use of artificial intelligence in green logistics requires not only technical capacity but also organizational and managerial maturity.

In conclusion, artificial intelligence is considered not merely a supporting technology in green logistics, but a fundamental transformative tool enabling the achievement of sustainability goals. The conceptual framework presented in this section provides a theoretical and methodological foundation for the AI-based optimization techniques that will be discussed in the next subsection.

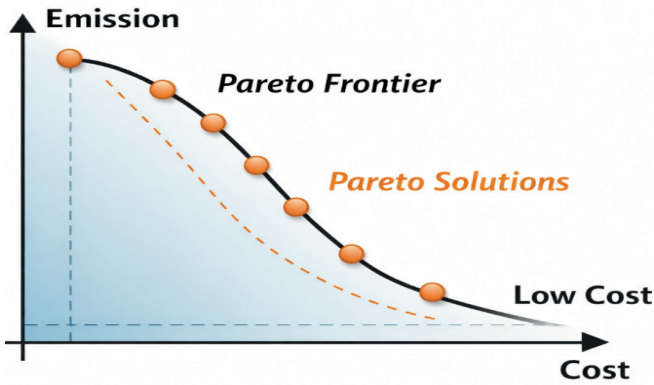
## **2. Artificial Intelligence-Based Optimization Techniques**

Decision-making processes in green logistics systems require the consideration not only of economic performance but also of environmental and operational sustainability. Goals such as reducing transportation costs, improving delivery times, and lowering carbon emissions often exhibit conflicting structures. This transforms logistics decision problems into a multi-objective, complex, and nonlinear structure. Classical deterministic optimization methods are practically insufficient in such problems due to the size of the solution space and uncertainties. Therefore, artificial intelligence-based optimization approaches are increasingly used in the literature for solving green logistics problems.

AI-based optimization methods enable the integration of environmental criteria directly into decision models, thus integrating green logistics goals with operational decisions. This section discusses multi-objective optimization problems in green logistics, meta-heuristic algorithms used for these problems, and the integrated use of artificial intelligence and optimization.

### **2.1. Multi-Objective Optimization Problems in Green Logistics**

Optimization problems addressed within the context of green logistics are, by their nature, defined within the framework of multi-objective decision-making. In logistics systems, decision-makers must consider not only cost minimization but also performance metrics such as energy consumption, carbon emissions, and service level simultaneously. This makes optimization approaches based on a single objective function insufficient. In multi-objective optimization problems, multiple performance criteria such as cost, carbon emissions, and energy consumption are attempted to be optimized at the same time. In such problems, solution results are generally obtained in the form of Pareto optimal solution sets. Pareto optimal solutions represent a solution set where at least one other objective deteriorates while one objective is improved. A representative illustration of the Pareto solution space within the scope of multi-objective optimization in green logistics is presented in Figure 3.



*Figure 3. Pareto solution space in multi-objective optimization in green logistics*

Common multi-objective optimization problems in green logistics include vehicle routing, fleet planning, warehouse location selection, inventory optimization, and supply chain network design. These problems often involve a trade-off relationship between metrics such as cost, time, energy consumption, and carbon emissions. For example, faster delivery often means higher fuel consumption and emissions, making the decision-making process more complex.

In this context, multi-objective optimization approaches offer Pareto-optimal solution sets instead of a single “best” solution, allowing decision-makers to compare different sustainability scenarios and make strategic choices. Current literature emphasizes that considering environmental performance indicators alongside operational and economic goals is critical for the effectiveness of green logistics systems (Baryannis et al., 2019; Garside et al., 2024).

## 2.2. The Use of Meta-Heuristic Algorithms in Green Logistics

Due to the complex and multidimensional nature of green logistics problems, meta-heuristic algorithms are the most widely used AI-based optimization methods in the literature. These algorithms aim to obtain high-quality solutions within acceptable computation times, rather than producing exact solutions.

**Genetic Algorithms (GAs)** are optimization methods inspired by the process of biological evolution. Possible solutions are evaluated as a population, and solutions with better performance are improved through evolutionary operators to generate new solutions. GAs are widely preferred, especially in multi-objective green logistics problems, due to their ability to preserve solution diversity and create Pareto-optimal solution sets.

**Particle Swarm Optimization (PSO)** is an approach inspired by the collective behavior of organisms moving in swarms. In PSO, each solution candidate progresses through the solution space by learning from both its own past experiences and the best solution of the swarm. This structure allows PSO to achieve rapid convergence, especially in problems such as fleet management and route optimization.

**Ant Colony Optimization (ACO)** is an algorithm based on the behavior of ants finding the shortest path through pheromone trails. ACO focuses on good solutions in network-based problems, generating more efficient routes over time. This feature makes ACO a suitable method for dynamic green logistics problems such as vehicle routing and urban distribution.

The flexible structure of meta-heuristic algorithms allows for the direct integration of environmental criteria into objective functions or constraints, making these algorithms powerful decision support tools for green logistics applications.

### **2.3. Integrated Use of Artificial Intelligence and Optimization**

Recent studies have shown that the integrated use of machine learning and optimization algorithms in green logistics problems offers significant advantages. This approach makes it possible to model the uncertain and dynamic nature of logistics systems more realistically.

In this integrated structure, machine learning models are used in processes such as demand forecasting, travel time prediction, energy consumption estimation, and maintenance needs assessment. These predictions provide more realistic and up-to-date inputs for optimization models, improving decision quality. For example, improved demand forecasting contributes to reducing unnecessary transportation activities and excessive capacity utilization, thereby reducing environmental impacts.

Optimization algorithms use these inputs generated by machine learning to determine decision variables such as route planning, fleet allocation, and resource allocation. This structure enables green logistics systems to become more adaptable and flexible, especially under changing traffic conditions, fluctuating demand structures, and uncertain operational environments.

In the literature, this approach is referred to as data-driven optimization or learning-assisted optimization and is considered a crucial component of sustainable decision-making processes in green logistics. Current systematic studies show that the integrated use of machine learning and optimization has positive effects on both economic and environmental performance (Toorajipour et al., 2021; Culot et al., 2024).

## 2.4. Optimization Problems and Application Examples for Green Logistics

Artificial intelligence-based optimization techniques can be applied to numerous problem types arising at different decision levels within the scope of green logistics. These problems encompass strategic, tactical, and operational decisions aimed at reducing the environmental impact of logistics activities. A common feature of green logistics optimization problems discussed in the literature is that they require the simultaneous evaluation of economic and environmental goals and generally have a multi-objective structure. In this context, the main green logistics optimization problems are summarized below:

- **Green Vehicle Routing Problem (GVRP):** This is one of the most intensively studied problem classes in the green logistics literature. It is an extended version of the classic vehicle routing problem, taking into account fuel consumption, carbon emissions, vehicle types, and environmental constraints. The aim is to determine routes that minimize both total cost and environmental impact. Current studies show that GVRP can be effectively solved with multi-objective meta-heuristic and hybrid AI approaches (Moghdani et al., 2021; Asghari & Mirzapour Al-e-hashem, 2021).

- **Energy Efficient Fleet Planning Problems:** This class of problems aims to optimize fleet size, vehicle types (conventional, hybrid, electric), and usage rates considering energy consumption and emissions. The integration of alternative fuel vehicles into logistics systems, in particular, makes these problems strategically important. AI-based optimization approaches allow for the determination of fleet composition in a way that is consistent with environmental goals (Kucukoglu et al., 2021).

- **Green Facility Location and Warehouse Site Selection Problems:** These problems aim to determine the locations of warehouses and distribution centers in a way that minimizes transportation distances, energy consumption, and carbon footprint. This type of problem directly affects the environmental dimension of supply chain network design. Multi-objective optimization models clearly reveal the balance between cost and emission targets, offering decision-makers the opportunity to evaluate alternative network structures (Dukkanci et al., 2019; Liu et al., 2021).

- **Inventory and Stock Management Optimization:** This class of problems, aimed at preventing overproduction, unnecessary stockpiling, and waste generation, holds a significant place in the operational dimension of green logistics. Thanks to optimization approaches integrated with demand forecasting, stock levels are managed more effectively; this contributes to reducing energy consumption and environmental impacts (Sebatjane, 2025).

- **Intra-City Distribution and Last Mile Logistics Optimization:**

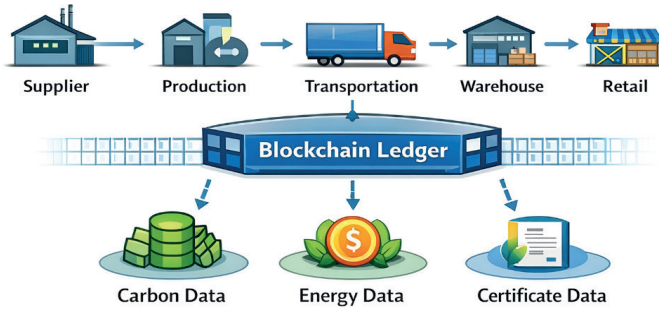
This class of problems, which considers environmental factors such as traffic density, time windows, emission constraints, and noise, is particularly important for sustainable urban logistics. Artificial intelligence-based optimization techniques enable the creation of distribution plans that minimize environmental impacts under dynamic conditions (Bosona, 2020; Shuaibu et al., 2025).

These examples demonstrate that AI-based optimization techniques can be applied to a wide range of problems in green logistics applications, and that environmental sustainability goals can be effectively integrated into operational decisions. Therefore, these approaches are among the fundamental decision support tools in the design and operation of green logistics systems.

### **3. Supply Chain Transparency with Blockchain Technology**

Digital transformation has not only increased efficiency in logistics and supply chains but has also made governance dimensions such as transparency, traceability, and trust critical. Especially in the context of green logistics, managing environmental impact data (e.g., energy consumption, carbon emissions, sustainable supply claims) in a verifiable and auditable manner throughout the product's journey from raw materials to final delivery is crucial for the reliability of sustainability performance. Blockchain technology, through its distributed ledger approach, provides an infrastructure that strengthens transparency in the supply chain by enabling the immutable recording of data and the generation of consensus among stakeholders (Sunny et al., 2020; Dasaklis et al., 2022).

In green logistics applications, the value of blockchain stands out on two main axes: (i) standardization of traceability (who did what, where, and when?) and (ii) reliability of reported sustainability data (which metric is proven by which data?). However, the widespread adoption of blockchain solutions in real-world applications is not always “easy” due to obstacles such as scalability, data privacy, integration costs, and governance. Studies examining blockchain adoption barriers in sustainable supply chains clearly highlight these limitations (Kouhizadeh et al., 2021). The data flow structure and verifiable monitoring of environmental performance data in blockchain-based sustainable supply chains are shown in Figure 4.



*Figure 4. Data verification and traceability structure in a blockchain-based sustainable supply chain*

This section systematically addresses the contribution of blockchain to supply chain transparency, its main application areas in green logistics, the automation dimension with smart contracts, IoT/AI integrated architectures, limitations, and future research directions.

### 3.1. The Basic Structure and Working Principle of Blockchain Technology

Blockchain is a distributed database architecture where transactions are recorded in data packets called “blocks,” and each block is linked to the previous block using cryptographic methods. The main purpose of this structure is to enable stakeholders to agree on the same transaction record without the need for a central authority. This agreement is achieved through different consensus mechanisms (e.g., Proof-of-Work, Proof-of-Stake, or alternative consensus protocols used in permissioned networks) depending on the network structure. Current studies show that blockchain is moving beyond financial applications and transforming into an enterprise digital infrastructure technology in multi-stakeholder industrial processes such as production, logistics, and supply chain coordination (Choi & Siqin, 2022; Dasaklis et al., 2022).

Blockchain-based supply chain applications typically include the following key components:

- **Distributed Ledger Technology (DLT):** Enables the synchronization of transaction records among network participants. This structure enhances data integrity and transparency, contributing to trust among supply chain stakeholders (Rejeb et al., 2021).

- **Immutability:** The blockchain architecture makes it difficult to retrospectively alter transaction records without authorization. This feature is particularly critical for supply chain traceability and sustainability reporting (Dasaklis et al., 2022).

- **Smart Contracts:** Programmable digital protocols that execute automatically under specific conditions and enforce predefined business rules. In supply chain applications, smart contracts increase the automation and reliability of operational processes (Grida & Mostafa, 2023).

- **Identity and Authorization Mechanisms:** These enable the management of data access rights, especially in permissioned blockchain networks. This structure plays a critical role in protecting commercially sensitive data (Kouhizadeh et al., 2021).

From a green logistics perspective, the most critical feature of blockchain technology is not that it automatically guarantees the accuracy of data; rather, it enables transparent tracking of who recorded the data, when, and through what process. Therefore, the true impact of blockchain applications should be evaluated in conjunction with the quality of the data entering the chain, data verification mechanisms, and stakeholder governance structures. This is described in the literature as the “oracle problem,” emphasizing the necessity of reliable verification mechanisms in the transfer of data from the physical world to digital record systems (Rejeb et al., 2021; Dasaklis et al., 2022).

### 3.2. Carbon Footprint and Sustainability Monitoring

In green logistics applications, accurate and reliable monitoring of the carbon footprint is considered one of the fundamental elements of sustainable supply chain management. The multi-layered and multi-stakeholder structure of global supply chains significantly complicates the collection, verification, and reporting of carbon emission data. In particular, the measurement of indirect emission sources, defined as Scope 3 emissions, requires data integration from different supply chain actors and brings with it data reliability issues. In this context, blockchain technology is considered an important digital infrastructure that increases data integrity in carbon footprint monitoring by enabling the immutable recording of emission data (Kouhizadeh et al., 2021).

Blockchain-based carbon monitoring systems allow for the transparent monitoring of emission data related to production, transportation, storage, and distribution activities throughout the supply chain. Thanks to these systems, stakeholders can track the source and accuracy of carbon emission data; this increases the reliability of sustainability reporting. The literature emphasizes that blockchain-based traceability systems play a significant role in verifying sustainability performance, particularly in low-carbon supply chain applications (Zhang et al., 2024).

Sustainability tracking encompasses not only the measurement of carbon emissions but also the monitoring of energy consumption, resource use, and environmental compliance criteria. Blockchain technology contributes to sustainable supply chain management by enabling the standardized and

verifiable storage of this data throughout the supply chain. The effectiveness of blockchain-based systems is increasingly evident, particularly in verifying sustainable supply certificates and reporting environmental performance indicators (Dasaklis et al., 2022).

However, the effectiveness of blockchain technology in carbon footprint tracking depends not only on the technological infrastructure but also on the reliability of data verification processes. The accuracy of emission data obtained from the physical world is directly related to sensor technologies, IoT infrastructures, and data verification mechanisms. This is referred to as the “oracle problem” in the literature, highlighting the critical role of data verification processes in blockchain-based sustainability monitoring systems (Rejeb et al., 2021).

In conclusion, blockchain technology contributes to the development of sustainable logistics systems by increasing data transparency and traceability in carbon footprint and sustainability tracking. However, the effective use of this technology depends on the development of data quality, stakeholder collaboration, and standard data sharing protocols.

### **3.3. Transparent, Traceable, and Reliable Supply Chains**

The increasing complexity of global supply chains, multi-layered supplier structures, and geographically dispersed production networks have made supply chain transparency a critical determinant of sustainability performance. Especially in the context of green logistics, the verifiable tracking of environmental impacts throughout the process from raw materials to the end consumer is crucial for corporate sustainability strategies and regulatory compliance. At this point, blockchain technology offers a digital infrastructure that strengthens transparency and traceability by enabling the immutable recording of transactions throughout the supply chain (Saberli et al., 2019; Sunny et al., 2020).

Blockchain-based traceability systems reduce information asymmetry by standardizing data sharing among supply chain actors and contribute to the building of trust among stakeholders. Particularly in sustainable supply chain applications, the effectiveness of blockchain-based solutions is increasing in processes such as product origin verification, sustainable raw material certification, and carbon emission data verification (Kouhizadeh et al., 2021).

However, supply chain transparency is not solely dependent on technological infrastructure. Governance elements such as data quality, stakeholder collaboration, and data standardization also determine the effectiveness of blockchain-based traceability systems. Therefore, the success of blockchain technology in sustainable supply chain applications requires a combined approach to technological infrastructure and organizational governance mechanisms (Choi & Siqin, 2022).

### 3.4 Smart Contracts and Green Certification

Smart contracts are blockchain-based software protocols that automatically execute when predefined conditions are met and implement business rules in a digital environment. In supply chain management, smart contracts are used particularly in processes such as delivery verification, quality control, certificate verification, and payment automation (Casino et al., 2019).

In the context of green logistics, smart contracts provide significant advantages in terms of verifying sustainability certificates and automatically auditing environmental compliance criteria. For example, products from a supplier with a sustainable production certificate can be automatically verified through certificate data recorded on the blockchain, and the transaction can be automatically stopped if the certificate conditions are not met. This increases the reliability of audit processes in sustainable supply chain practices (Kouhizadeh et al., 2021).

Furthermore, smart contracts can also be used in the implementation of performance incentive mechanisms based on carbon emission targets. For example, automatic incentive payments can be made to suppliers who produce below certain emission limits, or automatic warning mechanisms can be activated for high carbon-intensive processes. This structure facilitates the integration of sustainability performance into operational decision-making processes (Saberli et al., 2019).

However, the effective implementation of smart contracts in sustainable supply chains depends on factors such as data accuracy, standard certification data models, and regulatory compliance. In particular, the application of different sustainability standards in different geographic regions creates significant challenges in the design of smart contract-based certification systems (Choi & Siqin, 2022).

### 3.5 Limitations in Blockchain-Based Green Logistics Systems

Although blockchain technology offers significant potential in areas such as supply chain transparency, sustainability data verification, and carbon footprint tracking, it faces various technical and organizational limitations in real-world applications. These limitations primarily include technical challenges such as scalability, energy consumption, data privacy, and system integration. The performance and transaction costs of blockchain-based systems remain a significant area of research, especially in high-volume global supply chains (Saberli et al., 2019).

Another critical challenge in blockchain-based sustainability monitoring systems is the accuracy of data transferred from the physical world to digital systems. This situation, referred to in the literature as the “oracle problem,”

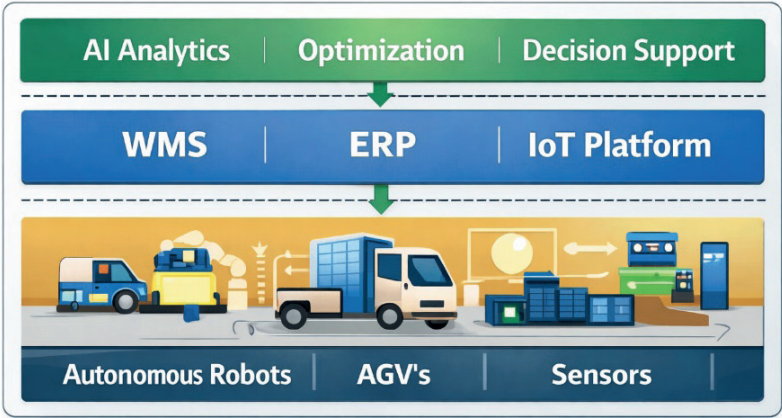
reveals the dependence of blockchain systems on the data source. In particular, the transfer of carbon emission data to the system via sensors, IoT devices, or manual data entry makes data verification processes critically important (Rejeb et al., 2021).

From an organizational perspective, the widespread adoption of blockchain technology in supply chains depends on governance elements such as stakeholder data sharing, the creation of standard data formats, and regulatory compliance. Especially in sustainable supply chain applications, the application of different environmental standards in different geographies makes standardization of blockchain-based systems difficult (Kouhizadeh et al., 2021).

From a future research perspective, the integration of blockchain technology with other digital technologies offers significant opportunities. In particular, blockchain architectures integrated with IoT sensor technologies, big data analytics, and AI-based decision support systems are expected to offer more effective solutions in sustainable supply chain management. These integrated digital architectures are projected to make significant contributions in areas such as sustainability data validation, operational optimization, and real-time sustainability performance monitoring (Choi & Siqin, 2022). In conclusion, blockchain technology provides a powerful digital infrastructure for sustainable and transparent supply chain management. However, the technology's ability to effectively contribute to sustainability goals depends on the development of data quality, governance structures, standardization, and multi-stakeholder collaboration mechanisms.

#### **4. Smart Warehouses and Autonomous Logistics Systems**

The increasing e-commerce volume in the logistics sector, customer-centric delivery expectations, and the complexity of global supply chains have made warehouse systems one of the most critical nodes in logistics networks. Traditional warehouse systems are characterized by structures largely reliant on manual operations, offering limited data visibility and limited optimization possibilities in terms of sustainability. However, digital technologies developed within the framework of the Industry 4.0 paradigm have enabled the redesign of warehouse operations through automation, data analytics, and artificial intelligence-supported decision-making mechanisms.



*Figure 5. AI-powered smart warehouse cyber-physical system architecture*

Smart warehouse systems, emerging from this transformation process, aim not only to increase operational efficiency but also to contribute to green logistics goals such as reducing energy consumption, lowering carbon emissions, and optimizing resource use. Smart warehouses are considered cyber-physical systems integrating sensor technologies, robotic systems, artificial intelligence algorithms, and advanced software platforms (Boysen et al., 2019; Winkelhaus & Grosse, 2020). Figure 5 shows the AI-supported smart warehouse cyber-physical system architecture and the integration of analytics, optimization, decision support, WMS, ERP, IoT platforms, and autonomous warehouse technologies within this structure.

**4.1. Smart Warehouse Concept and Basic Components**

The smart warehouse concept refers to a warehouse management approach where warehouse operations are managed automatically, data-driven, and adaptively by integrating digital technologies. In this approach, the warehouse is not merely a physical storage area but a dynamic system that generates real-time data and allows for decision-making based on this data.

One of the fundamental components of smart warehouse systems is the data collection infrastructure. Through RFID tags, IoT sensors, barcode systems, and image processing technologies, the location, movement, and status of products can be continuously monitored. This real-time data flow enables warehouse management systems (WMS) to make accurate and rapid decisions (Kache & Seuring, 2017).

Another critical component is warehouse management software. Modern WMS solutions go beyond classic inventory tracking functions, offering advanced functions such as order picking optimization, in-warehouse route planning, workforce planning, and performance analytics. When integrated

with artificial intelligence and data analytics algorithms, this software allows for the dynamic optimization of warehouse operations (Winkelhaus & Grosse, 2020).

The success of smart warehouse systems also depends on their ability to integrate with other systems. Integration with ERP, TMS, and supply chain management systems increases end-to-end supply chain visibility and strengthens operational coordination. This integration is particularly critical for measuring and reporting sustainability performance.

#### **4.2. Autonomous Vehicles and Robotic Warehouse Systems**

Autonomous logistics systems encompass robotic systems where operations such as in-warehouse handling, product placement, and order picking are performed without human intervention or with minimal human interaction. These systems significantly increase operational efficiency, particularly in large-scale and high-volume warehouse operations.

Autonomous mobile robots (AMR) and automated guided vehicles (AGVs) are widely used to automate in-warehouse handling operations. These vehicles can create safe and optimized movement routes by sensing the warehouse environment through sensor technologies, lidar systems, and computer vision algorithms (Boysen et al., 2019).

The integration of robotic systems into warehouse operations increases order picking accuracy, shortens operation times, and reduces human error. Furthermore, robotic systems contribute to reduced energy consumption by optimizing in-warehouse traffic. The literature emphasizes the potential of robotic warehouse systems to reduce the carbon footprint of warehouse operations (De Koster et al., 2017).

#### **4.3. Energy-Efficient Warehouse Management**

Warehouse operations result in high energy consumption due to lighting, climate control, automation equipment, and robotic systems. Energy-efficient warehouse management encompasses strategic and operational approaches aimed at minimizing this energy consumption.

Smart lighting systems reduce unnecessary energy use through motion sensors and daylight-sensitive control mechanisms. Similarly, smart climate control systems reduce energy consumption by optimizing in-warehouse temperature and humidity levels based on real-time sensor data (Zhang et al., 2018).

The energy consumption of robotic systems can also be optimized with artificial intelligence-based planning algorithms. Route planning and task allocation of autonomous robots can be dynamically adjusted to minimize energy consumption. This approach is considered a significant factor in increasing the sustainability of warehouse operations.

#### **4.4. AI-Powered Inventory Management and Shelf Optimization**

AI-based inventory management systems play a central role in optimizing warehouse operations. Machine learning algorithms support demand forecasting and inventory planning decisions by analyzing historical demand data, seasonality effects, and operational performance indicators (Albayrak et al., 2023).

In shelf optimization applications, AI algorithms optimize the positions of products within the warehouse based on order frequency, product weight, delivery priorities, and ergonomic criteria. This optimization reduces movement distances within the warehouse, thereby increasing operational efficiency and reducing energy consumption.

Dynamic slotting applications stand out as a significant component of AI-powered warehouse management. In these applications, product placement is continuously updated according to real-time demand changes, and warehouse space utilization is optimized (Boysen et al., 2019).

In summary, smart warehouse systems are critical components that enable the implementation of sustainable logistics practices at the operational level. Reducing internal warehouse transport distances, optimizing energy consumption, and preventing unnecessary stock movements directly contribute to reducing carbon emissions. Furthermore, smart warehouses offer important data infrastructures for measuring and reporting sustainability performance. Digital monitoring of warehouse operations enables more accurate and transparent reporting of environmental performance indicators. In the future, smart warehouse systems are expected to become more integrated with digital twin technologies, autonomous logistics networks, and AI-based decision support systems. This integration will contribute to making logistics systems more sustainable, more flexible, and more efficient.

#### **5. Future Perspective and Open Research Areas**

Today, logistics and supply chain systems are transforming from structures focused solely on operational efficiency into complex socio-technical systems based on data-driven, autonomous, and sustainable decision-making mechanisms. The rapid development of digitalization, automation, and artificial intelligence technologies is fundamentally changing the design, management, and optimization of logistics processes. In this transformation process, digital twin technologies, autonomous logistics networks, and AI-powered decision systems stand out as fundamental building blocks of the future logistics ecosystem (Le & Fan, 2024; Xu et al., 2024). However, the widespread adoption of these technologies brings not only technical opportunities but also new research areas such as data security, system resilience, ethical decision-making mechanisms, and the integration of sustainability goals into technology design processes. This section

examines the key digital technologies expected to shape the future of logistics systems and the open research areas related to these technologies, from both conceptual and technical perspectives.

### 5.1. Digital Twins: Virtual Reality and Decision Support Systems in Logistics

Digital twins, as digital reflections of physical systems, offer real-time monitoring, simulation, and optimization capabilities in logistics and supply chain management. This technology, integrated with IoT sensors, artificial intelligence algorithms, and big data analytics, is used across a wide range of processes, from warehouse operations to transportation (Le & Fan, 2024).

The main applications of digital twins in logistics are:

- **Warehouse Optimization:** Used to analyze and optimize warehouse structures. Sensors record inventory data in real time, enabling optimal utilization of warehouse capacity and automated reordering processes.
- **Transportation Route Simulation:** Routes are analyzed and optimized taking into account current traffic conditions, weather conditions, and delivery priorities. This reduces transportation times and lowers costs.
- **Supply Chain Management:** Companies can simulate and optimize their entire supply chain using digital twins. By identifying risks such as delays or material bottlenecks at an early stage, better planning and supply chain resilience are ensured.

Ensuring data quality, integration with existing systems, and continuous optimization are crucial for the effective use of digital twins. This technology contributes to making logistics processes more efficient, transparent, and sustainable.

### 5.2. Autonomous Logistics Networks: Self-Managing Supply Chains

Autonomous logistics networks aim to manage logistics processes without the need for human intervention through the integration of artificial intelligence, IoT, robotics, and advanced analytics technologies. These systems create flexible, scalable, and resilient supply chains thanks to their real-time data analysis and decision-making capabilities (Xu et al., 2024).

The key features of autonomous logistics systems are:

- **Real-Time Visibility:** Offers instant monitoring and analysis at every stage of the supply chain thanks to IoT sensors and artificial intelligence algorithms.
- **Dynamic Decision Making:** Can make instant decisions and optimize processes by evaluating signals such as demand changes, external risks, and IoT data.

- **Human-Robot Collaboration:** Autonomous systems take over routine tasks, while humans participate in strategic decision-making and oversight processes.

The success of these systems depends on factors such as data quality, system integration, and security measures. Autonomous logistics networks will contribute to more efficient and sustainable logistics operations in the future.

### 5.3. Ethical and Security Dimensions of Artificial Intelligence in Green Logistics

Artificial intelligence makes significant contributions to green logistics applications in areas such as energy efficiency, emission reduction, route optimization, warehouse energy management, and improved resource utilization. Big data analytics and machine learning algorithms offer powerful decision support mechanisms for measuring and reducing the environmental impact of logistics operations. However, the widespread adoption of AI-based systems necessitates evaluation not only in terms of technical performance but also in terms of ethics, governance, and security. Designing AI systems in a transparent, reliable, and responsible manner is critical for effectively achieving sustainability goals in green logistics.

The concept of ethical artificial intelligence refers to the development of transparent, fair, traceable, and accountable algorithmic systems that contribute to environmental, social, and economic sustainability goals. In the context of green logistics, ethical AI applications encompass not only operational efficiency but also elements such as accurate measurement of environmental impacts, reliable reporting of sustainability data, and fair data usage among supply chain stakeholders. In this context, data privacy, prevention of algorithmic bias, explainability of decision-making processes, and algorithmic transparency stand out as important ethical requirements (Samadhiya et al. 2025).

Since AI systems used in green logistics operate with large amounts of operational and environmental data, data security and data privacy become critical. Protecting sensitive information, especially carbon emission data, operational performance data, and supplier sustainability data, is crucial for both business security and legal compliance. Therefore, secure data management, cybersecurity protocols, and the development of reliable data sharing infrastructures are fundamental requirements for the sustainability of AI-based logistics systems.

From a security perspective, protecting AI systems against cyberattacks, ensuring data integrity, and increasing the operational resilience of the systems are critically important. In particular, protecting the algorithms

used in autonomous logistics systems against manipulation and maintaining human oversight in critical decision-making processes contributes to reducing ethical and security risks. Accordingly, ethical governance, secure data infrastructures, and algorithmic transparency principles must be considered together in the design of AI systems in green logistics.

### **Conclusion**

This chapter examines the role of artificial intelligence, optimization techniques, blockchain technology, and smart logistics systems in the green logistics transformation from a holistic perspective. Today's logistics systems are evolving from cost and service level-focused structures towards data-driven and intelligent decision-making systems that prioritize environmental sustainability. In this transformation process, artificial intelligence, thanks to its predictive analytics, dynamic optimization, and autonomous decision-making capabilities, both increases operational efficiency and contributes to environmental goals such as reducing carbon emissions, increasing energy efficiency, and optimizing resource use.

The artificial intelligence approaches and multi-objective optimization models discussed in this chapter make it possible to evaluate conflicting performance criteria such as cost, time, energy consumption, and carbon emissions together. Blockchain technology, on the other hand, offers a significant digital infrastructure in terms of supply chain transparency, verification of sustainability data, and carbon footprint tracking. However, the effectiveness of these technologies depends on the development of data quality, stakeholder collaboration, and standard data sharing mechanisms.

Smart warehouses, robotic systems, autonomous logistics networks, and digital twin technologies stand out as fundamental structures supporting the operational-level implementation of green logistics. However, the success of digital technologies in green logistics depends not only on technical capacity but also on multi-dimensional factors such as data governance, ethical artificial intelligence, cybersecurity, and organizational transformation.

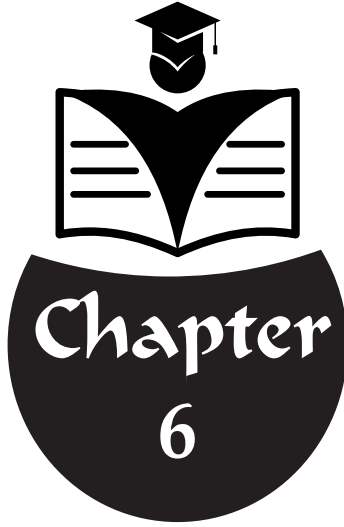
In conclusion, the integration of artificial intelligence, optimization, blockchain, and smart logistics systems is creating a new paradigm in the design of sustainable logistics systems. In the future, the success of green logistics systems will depend not only on the technical performance of digital technologies but also on multi-stakeholder collaboration, data standardization, and the development of sustainability-focused governance models.

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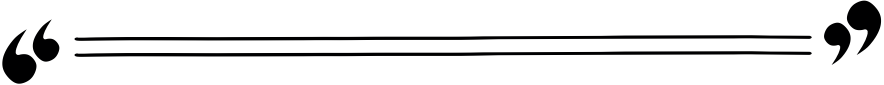
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**BIG DATA-ENABLED GREEN LOGISTICS:  
SMART SYSTEMS, OPTIMIZATION, AND  
SUSTAINABILITY PERFORMANCE**



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## Introduction

The global logistics sector faces rising carbon emissions, energy consumption, and environmental pressures, parallel to the growth of global trade. The carbon footprint of logistics operations, particularly greenhouse gas emissions from road transport, has become central to the environmental sustainability agenda; this necessitates a reassessment of logistics activities not only in terms of economics but also environmental performance (McKinnon, 2018; Dekker et al., 2012).

To respond to net-zero targets and sustainability expectations, the sector is adopting data-driven management approaches while optimizing operational processes. With digital transformation, the integration of data-intensive technologies, and the widespread adoption of smart systems, logistics activities have become more agile, flexible, and environmentally measurable. In this context, big data, by providing real-time visibility into logistics networks, not only strengthens operational decision-making mechanisms but also plays a central role in taking sustainability performance to a strategic level (Hongsakul et al., 2025). However, the digital transformation of logistics constitutes technological investment and organizational and managerial transformation. Tran-Dang et al. (2025) emphasize that data-driven technologies are a strategic tool for improving operational efficiency and carbon performance in the logistics sector. This study reveals that digital transformation is not only a technological process but also necessitates managerial transformation.

This study is positioned at three levels in the literature. First, the cost-time-carbon trade-off, which is mostly addressed in the green logistics literature with static optimization models based on operational research, is examined in an integrated manner with big data infrastructure and real-time decision-making mechanisms. Thus, sustainable logistics decisions are restructured within a data-driven and dynamic management framework, moving beyond mathematical modelling problems. Second, the effects, generally examined in the context of performance and agility in the big data analytics literature, are directly linked to sustainability performance indicators (carbon intensity, energy efficiency, empty kilometer ratio, etc.), providing a conceptual framework. Third, the integration of multi-objective optimization outputs into enterprise sustainability management is addressed within the framework of a decision intelligence approach, proposing a holistic framework that bridges analytical models and strategic governance.

This book chapter is structured as follows: First, the conceptual foundations of big data-driven green logistics are presented, and sustainability literature and the big data analytics approach are integrated within a theoretical framework. Next, the big data infrastructure and carbon-aware data architectures that form the technical backbone of sustainable logistics systems

are discussed. The third section discusses the role of big data-driven smart systems in application areas such as route planning, demand forecasting, and fleet management. The fourth section examines multi-objective optimization models based on cost-time-carbon trade-off; and the fifth section evaluates the integration of optimization outputs into sustainability performance indicators and decision intelligence processes. Finally, the key challenges in the implementation process and future research directions for carbon-neutral and adaptive logistics networks are addressed. In this chapter, the term “big data-enabled” refers to the infrastructural role of data ecosystems, while “big data-driven” emphasizes the analytical and decision-centric transformation of logistics systems.

### 1. Conceptual Foundations of Big Data-Enabled Green Logistics

Green logistics encompasses strategic and operational practices aimed at reducing the environmental impact of logistics activities. Supply chain activities, particularly transportation and logistics, are central to the sustainability agenda because of their impact on fuel consumption, greenhouse gas emissions, noise, waste, and energy intensity. The findings indicate that transportation-related CO<sub>2</sub> emissions account for a significant share globally, with transportation accounting for approximately 24% when only energy-related CO<sub>2</sub> is considered (Ritchie, 2020; Foster & Lebrand, 2023). This reality transforms “green logistics” from an optional operational strategy into a compulsory mandate for the industry.

The “green logistics” framework is deeply rooted in the **Triple Bottom Line (TBL)** concept originally proposed by Elkington (1998) and later operationalized within the logistics literature by Carter and Rogers (2008). As a multidimensional framework, TBL evaluates business success not only by economic output (profit/cost) but also through environmental (emissions, energy, resource use) and social (occupational health, safety, social impact) dimensions. This perspective moves the performance of logistics systems beyond the traditional “cost-speed” dichotomy, transforming it into a multi-target set of “cost-speed-carbon/energy” parameters (Jeurissen, 2020). This framework is also supported in the sustainable supply chain management literature, where the triggers of sustainability are conceptualized through supplier management and sustainable product/flow strategies (Seuring & Müller, 2008; Nagy & Szentesi, 2024).

With the acceleration of digital transformation, green logistics practices have evolved from “well-intentioned environmental initiatives” into data-driven programs that require measurable performance management. Smart logistics systems (IoT, sensor networks, GPS-based tracking, blockchain, cloud, and edge computing) play a critical role in this transformation (Nartey & Sasraku-Neequaye (2025)). The high volume and speed of data generated by smart systems

make it possible to report and manage environmental performance during operations. For example, when real-time traffic data is combined with speed profiles, driving/route decisions that have a direct impact on fuel consumption and, therefore, emission intensity can be dynamically updated.

Big data analytics (BDA) is a competency set that enables green logistics. Big data analytics generates value at three levels by linking logistics data (location, time, velocity, load, energy) to environmental goals (Wamba et al., 2020; Abbasi et al., 2024, Liu et al., 2020): (i) **descriptive analytics** that makes the current emission/energy profile visible; (ii) **predictive analytics** that foresees demand, delay, maintenance needs, and emission trends; and (iii) **prescriptive analytics** that derives decisions that establish the optimal balance between cost, time, and carbon. Studies examining the impact of this approach on outcomes such as supply chain performance and agility show that big data analytics strengthens performance and adaptability.

Another point highlighted in the literature regarding the focus on green logistics is that BDA improves environmental performance, not alone, but often in conjunction with complementary digital technologies and learning/organizational capabilities. For example, studies examining the relationship between the use of big data analytics, artificial intelligence, green supply chain collaboration and environmental performance emphasize the importance of digital learning and process integration (Benzidia, 2021; Gopal et al, 2024). Centobelli et al. (2020) demonstrated a relationship between green practices and “enabler technologies” (e.g., digitalization, data-driven monitoring) in logistics service providers (LSPs) and sustainable development goals. Wang and Yang (2022) showed that big data technology directly and indirectly enhances green logistics performance in manufacturing enterprises through supply chain integration. They revealed that BDA strengthens environmental performance through organizational integration.

Within the context of this book chapter, the concept of “Big Data-Enabled Green Logistics” can be examined as a three-layered conceptual whole as follows:

**1. Data and infrastructure layer:** Collection and governance of data such as GPS/telematics, warehouse energy sensors, traffic and weather flows, order and inventory time series, emission factors, etc.

**2. Analytical and optimization layer:** Demand forecasting, inventory optimization, multi-objective (cost-time-carbon) route planning, energy minimization, simulation, and digital twin approaches.

**3. Sustainability performance layer:** Improvements in indicators such as CO<sub>2</sub>/delivery, fuel consumption, idle mileage, tank energy intensity, and balance of service level and carbon.

This framework explains that big data is not inherently “green”; its green effect is generated through analytics, optimization and decision support mechanisms.

The Resource-Based View (RBV) from strategy perspective, data and analytical capabilities can be interpreted as a resource that can be transformed into a competitive advantage (Barney, 1991). However, maintaining green performance under dynamic environmental conditions (traffic, weather, demand fluctuations, and regulations) necessitates the integration of these analytical capabilities into operational decision-making systems.

Finally, conceptual studies that address the components of big data analytics (data processing, analytics, integration, security, etc.) and the dimensions of sustainability (transparency, culture, goals, risk management) together in the context of a sustainable supply chain emphasize that BDA requires a “technical infrastructure + managerial process” combination in sustainability management (Mageto, 2021). The following sections of this chapter will concretize the big data-enabled green logistics approach by connecting this conceptual foundation to patterns of logistics routing, demand forecasting, decision support and sustainability performance measurement.

## **2. Big Data Infrastructure for Sustainable Logistics Systems**

The effective design and management of sustainable logistics systems depend not only on operational improvements but also on data-driven environmental performance monitoring, analysis, and optimization mechanisms. Logistics activities have significant environmental impacts in terms of fuel consumption, greenhouse gas emissions, energy use, and waste production. Therefore, sustainable logistics requires systematic measurement, analysis, and minimization of environmental impacts. Big data infrastructure forms the technical and analytical basis of this process, not only in terms of the amount of data (Gupta et al., 2025).

The literature on sustainable supply chain management emphasizes the critical role of information flow and data transparency in improving environmental performance (Seuring & Müller, 2008). Today, this transparency is made possible by the use of big data infrastructures. Sustainability applications, such as emission measurement, energy monitoring, carbon intensity calculation, and resource efficiency analysis, cannot be effectively implemented without integrated data architectures (Zhang & Deng, 2024). Therefore, data lakes, cloud and edge computing solutions, and streaming data processing systems constitute the fundamental components of a sustainable logistics infrastructure.

## **2.1. Sustainability-Focused Data Ecosystem**

The data sources in big data-driven sustainable logistics systems are multi-layered and heterogeneous. Speed, fuel consumption, and route deviation data obtained from vehicle telematics systems, warehouse energy consumption and equipment performance information monitored through Internet of Things (IoT) sensors, traffic and weather streaming data, demand and order time series, and emission factors form the core components of this ecosystem. Integrating these data enables a holistic analysis of indicators such as carbon intensity (CO<sub>2</sub>/delivery), energy efficiency ratio, and the percentage of empty kilometers.

Centobelli et al. (2020) demonstrated that digital technologies, including big data applications, accelerate the adoption of green practices and contribute to sustainable development goals for logistics service providers. Similarly, Benzidia et al. (2021) show that big data analytics and artificial intelligence have significant and positive impacts on green supply chain collaboration and on environmental performance. These findings confirm that data infrastructure is the starting point of the chain leading to sustainable output.

## **2.2. Big Data Architectures and Environmental Performance**

The effectiveness of big data infrastructure in terms of sustainable logistics depends on the architectural design. Data lakes, cloud and edge computing solutions, and streaming data processing systems are the fundamental elements of this architecture.

### **2.2.1. Data Lakes and Integration Layer**

Data lakes are scalable storage structures that allow the storage of both structured and unstructured data in their raw form. In the logistics context, this structure enables the collection of carbon, energy, and operational data on a single platform. Thus, route-based emission analysis, warehouse-based energy intensity calculations, and vehicle-based carbon performance comparisons can be performed. Studies addressing the architectural and analytical dimensions of big data show that integrating different data types improves decision quality (Gandomi & Haider, 2015). From a sustainability perspective, this integration enables the evaluation of environmental performance at the system level rather than in a fragmented manner.

Bai and Sarkis (2020) emphasize that data analytics applications strengthen green supply chain performance and create strategic value, especially in terms of carbon intensity reduction. Therefore, data lakes are not only a storage solution but also the fundamental infrastructure for sustainability analytics.

### **2.2.2. Cloud, Edge Computing, and Real-Time Processing**

Cloud computing enables the scalable storage of high-volume logistics and environmental data and the execution of centralized analytical processes.

Analyses such as Environmental, Social, Governance (ESG) reporting and multi-warehouse and fleet comparisons can be performed efficiently. However, sustainability practices often require immediate interventions. Edge computing reduces delays by processing data near the source, thereby enabling applications such as real-time carbon optimization.

Ivanov and Dolgui (2021) demonstrated that digital supply chain twins and real-time data processing infrastructures enhance operational resilience and decision quality while providing a suitable simulation environment for sustainability analyses. In this context, data architecture is not merely a technical solution but a strategic tool that enables the management of environmental risks and carbon fluctuations.

Stream processing systems enable the continuous analysis of data, such as traffic density, speed variations, and fuel consumption. This allows dynamic route updates and prevents unnecessary emission increases. Dekker et al. (2012) demonstrated that operational research techniques make significant contributions to emission and energy minimization in green logistics. Xia (2025) reduced unit transport time by 38.75% and energy consumption by 23% through route optimization by integrating IoT-based data streams with SSA and Bi-GRU algorithms. Stream data infrastructures support the real-time implementation of these optimization models.

### **2.2.3. Analytical and Multi-Objective Optimization Layer**

The most significant contribution of big data infrastructure to sustainable logistics is that it enables the application of multi-objective optimization models. While traditional logistics optimization focuses on cost and time, the decision function in sustainable logistics expands jointly to include cost, time, carbon emissions, and energy consumption parameters.

Dubey et al. (2021) and Wamba et al. (2020) demonstrate that big data analytics capabilities have positive effects on sustainable performance and supply chain agility. These results reveal that data infrastructure is not merely a technical component, but a strategic sustainability capability that improves environmental performance. Wei (2025) proposed the Multi-Objective Grey Wolf Optimizer (MOGWO) algorithm, which simultaneously minimizes cost and carbon emissions in line with carbon neutrality targets. This study achieved higher emission reductions compared to traditional methods such as NSGA-II and PSO by directly integrating carbon emissions into the optimization model. Yin (2025) developed a genetic algorithm-based green deployment model that addresses carbon emission and cost minimization together, demonstrating that evolutionary algorithms are effective in route planning aligned with environmental goals. Chen (2024) developed route optimization models using particle swarm optimization algorithms and genetic algorithms that simultaneously minimized both cost and CO<sub>2</sub> emissions.

### **2.3. Carbon-Aware Data Design and Governance**

Sustainable logistics systems require a data infrastructure that systematically incorporates carbon parameters. The integration of emission factors into the data model, separate monitoring of Scope 1–2–3 emissions, and the definition of carbon intensity indicators are fundamental elements of this design. Bag et al. (2021) demonstrated that big data analytics supports operational excellence in sustainable supply chains and improves the environmental performance. Ye et al. (2022) showed that by developing a vehicle routing model that considers carbon emissions in time-variable road networks, the total carbon cost of the route can be reduced by 5.6%. However, sustainability reporting and ESG requirements render data accuracy critical. Data standardization, harmonization of emission calculation methodologies, traceability mechanisms, and cybersecurity measures play fundamental roles in ensuring the reliability of sustainability data. Seuring and Müller (2008) emphasized the central importance of transparency and traceability in sustainable supply chains. Big data infrastructure is the key tool that technically enables this transparency.

### **2.4. Impact on Sustainable Performance**

The literature shows a positive relationship between big data analytics and sustainable performance (Wamba et al., 2020; Dubey et al., 2021). This effect is manifested in ways such as reduced fuel consumption, decreased carbon intensity, increased energy efficiency, reduction of excess stock and waste, and emission minimization through route optimization. Therefore, big data infrastructure is not merely a supporting technology in sustainable logistics systems; it is a strategic sustainability backbone that enables carbon reduction, energy efficiency, and environmental performance optimization in the supply chain. Data lakes provide integration depth, cloud and edge computing deliver scalability and speed, and streaming data processing allows sustainability goals to be reflected in operational decisions in real-time.

## **3. Big Data–Driven Smart Systems in Green Logistics**

In green logistics, smart systems are not merely tools that digitize processes; they are socio-technical structures that enable the simultaneous management of environmental outputs, such as carbon emissions, energy consumption, and resource efficiency, with operational decisions. In this context, integrating big data (location-time-velocity-load-energy-emissions) flows with IoT, cloud/edge computing, and analytical models increases visibility, prediction, and optimization capabilities in logistics networks, enabling a shift from “reactive management” to “proactive and green optimization”. Findings demonstrating the positive impact of big data analytics on supply chain agility and operational performance reveal that smart systems strengthen the performance aspect while also providing critical infrastructure for achieving green logistics goals.

In green logistics, one of the highest environmental impact levers is transportation; therefore, the first and most visible application area of smart systems is real-time route and operation management. The “Logistics 4.0” approach, which combines traffic IoT infrastructure and big data predictive analytics, enables travel time estimation and real-time management, particularly in freight transportation. Chen et al. (2021) is an important reference in demonstrating how a big data-based predictive approach powered by traffic IoT infrastructure is positioned in real-time logistics management and generates value in the context of Logistics 4.0. Cao et al. (2022) showed that green route optimization is strengthened by integrating Smart-IoT infrastructure based on GPS, RFID, and load sensors into dynamic carbon emission vehicle routing models. Such systems support decision-making aimed not only at improving delivery performance through dynamic route updates, but also at reducing emission-increasing factors like stop-starts, idling times, and unnecessary deviations.

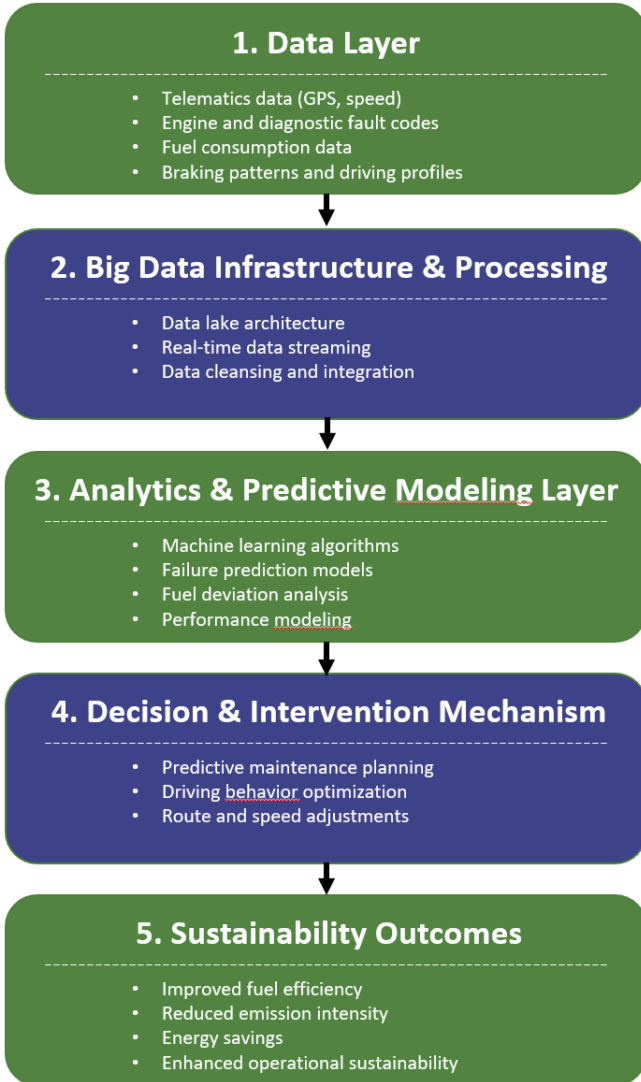
Green route planning demonstrates that the integration of environmental objectives (e.g., emission and energy minimization) into route optimization has a strong foundation in operational research literature. Environmental dimensions can be incorporated into transportation, inventory, and facility location decisions at both the planning and control levels (Dekker et al., 2012). In today’s data-driven smart systems, the real-time or near-real-time application of multi-objective functions, i.e., cost-time-carbon, is becoming increasingly important.

The second critical application area for smart systems in green logistics is demand forecasting and inventory optimization. Demand uncertainty can lead to negative sustainability consequences, such as excess inventory (increased energy consumption, additional storage needs, and risk of spoilage/waste) and shortages (urgent shipments, expedited transport, and associated increased emissions). The positive effects of big data analytics capabilities on supply chain agility and operational performance have been demonstrated in previous studies. This agility can indirectly contribute to reducing operational and environmental costs by enabling faster responses to fluctuating demand. Smart systems aim to increase forecasting accuracy and optimize predictive safety stock levels, dynamic reorder points, and distribution plans in an integrated manner with environmental goals.

In green logistics, the performance, technical condition, and driving behavior of a fleet play a decisive role. Therefore, processing data such as engine and fault codes, fuel consumption, braking profile, and speed fluctuations obtained from telematics systems through analytical models enables fleet maintenance processes to evolve from a reactive to a predictive approach. This transformation contributes to reducing inefficient driving and unplanned downtime due to breakdowns of vehicles. The application of machine learning in fleet operations has become increasingly widespread. In heavy vehicle fleets, the real-time processing of data flow and structuring of decision workflows are

becoming increasingly important (Brunheroto et al., 2022). Such analytical applications can indirectly contribute to reducing the emission intensity through improved fuel efficiency and operational performance.

From a green logistics perspective, data collection and analytical processing create a holistic value chain that feeds maintenance and operational decisions through diagnostics and predictive analyses. This chain ultimately establishes an impact mechanism that can create measurable improvements in energy consumption and carbon emissions. This is illustrated in Figure 1.



**Figure 1.** *Big Data–Driven Predictive Fleet Management for Green Logistics*

Smart systems are transforming not only real-time operational decisions but also scenario-based planning processes. The digital twin approach enables data-driven simulation, risk analysis, and decision evaluation by creating a digital representation of a supply chain network and its operations. In their study on the digital supply chain twin approach, Ivanov and Dolgui (2021) demonstrated that real-time network states can be represented and decision quality improved through the integration of model-based and data-driven methods. Digital twin applications from the green logistics perspective offer a powerful decision support framework that enables the analysis of alternative routes and demand scenarios along with their carbon and energy outputs, optimization of electric vehicle charging strategies, improvement of warehouse energy management, and evaluation of restructuring options with lower environmental impact in crisis conditions. However, the value creation of smart systems powered by big data in green logistics is not solely dependent on technological infrastructure; process integration and supply chain collaboration also play decisive roles. Empirical findings demonstrating that big data analytics and artificial intelligence applications strengthen environmental process integration and green supply chain collaboration, thereby improving environmental performance, reveal the organizational and managerial dimensions of the smart systems approach. Similarly, studies addressing green practices and enabling digital technologies together in logistics service providers show that digital transformation can make tangible contributions to sustainable development goals.

In summary, big data-driven smart systems create a three-layered impact mechanism in green logistics:

- Real-time monitoring and visibility (location-energy-emissions),
- Forecasting and optimization (routing, demand, maintenance),
- Sustainability performance outputs (CO<sub>2</sub> intensity, fuel/energy efficiency, empty kilometer ratio, waste reduction).

These layers through a feedback mechanism form a holistic structure that complements each other. While real-time monitoring data feed optimization models, the obtained results are measured using sustainability performance indicators and reintegrated into the system. Thus, green logistics has transformed from a static reporting approach into a dynamic data-driven management system.

#### **4. Multi-Objective Optimization for Cost–Time–Carbon Trade-offs**

In sustainable logistics systems, decision-making processes go beyond traditional single-objective optimization approaches. Classical logistics models are mostly based on cost minimization or delivery-time reduction. However, the increasing importance of climate change, carbon regulations,

and sustainability goals necessitates the integration of the environmental dimension into decision-making models. In this context, multi-objective optimization forms the analytical basis of green logistics within the framework of the cost-time-carbon balance.

Multi-objective optimization requires the simultaneous consideration of multiple and often conflicting objective functions. In logistics, these objectives typically include minimizing total costs, reducing delivery times, and lowering carbon emissions (McKinnon et al., 2015). Such problems are addressed within the framework of Pareto efficiency; that is, solutions are preferred in which improving one objective does not worsen the others.

Sbihi and Eglese (2010) emphasized that the inclusion of environmental objectives in mathematical models is becoming increasingly common in green logistics and distribution. Dekker et al. (2012), who comprehensively address the applications of operational research in green logistics, demonstrate that environmental dimensions can be integrated into models for transportation, inventory, and network design decisions, and that multi-objective models are an important tool in this field.

The optimization problem in sustainable logistics can be generally expressed as the minimization of the following requirements:

1. Total logistics cost
2. Delivery time delay
3. Total carbon emissions

Addressing these goals together enables decision-makers to develop balanced solutions that consider economic and environmental performance.

#### **4.1. Carbon Integrated Route and Network Optimization**

Transportation activities are among the most carbon-intensive components of logistics systems. Therefore, vehicle routing problems are significant in green optimization literature. Bektaş and Laporte (2011) integrated emission minimization into route decisions by modeling the relationship between speed, load, and fuel consumption within the framework of a pollution routing problem. This approach is important because it takes into account the fact that carbon emissions are not linear with distance and are affected by operational parameters. Demir et al. (2014) demonstrated that fuel consumption and emission reduction can be optimized along with cost targets by examining vehicle routing problems that consider the environmental criteria. These studies revealed that the cost-carbon balance can be mathematically modelled. With the advancement of big data infrastructure, such models have evolved from static planning tools into dynamic optimization systems that are fed by real-time traffic data, vehicle

sensor data, and weather information. Consequently, the cost–time–carbon balance can be updated during operations.

#### **4.2. Environmental Aspects in Demand Forecasting and Inventory Decisions**

Demand uncertainty can result in both economic and environmental losses. Overstocking can increase energy costs associated with storage and handling processes and, in particular, the risk of spoilage and waste (Becerra et al., 2022; Suvetha et al., 2025). On the other hand, insufficient inventory may raise environmental costs by triggering less efficient logistics practices, such as urgent or additional shipments, to maintain service levels (Sarkar, 2018). Therefore, demand forecasting and inventory optimization should be addressed from a multi-purpose perspective that considers both economic objectives and environmental impacts.

Studies demonstrating that big data analytics improves supply chain performance and agility (Wamba et al., 2020; Dubey et al., 2021) reveal that it enables faster responses to demand fluctuations. This agility can contribute to more efficient resource utilization management by increasing operational flexibility and indirectly improving environmental performance.

The literature on sustainable supply chain and logistics decisions emphasizes that stock levels and distribution frequency should be evaluated in conjunction with carbon output (Seuring & Müller, 2008; Dekker et al., 2012). In this context, the optimization model can be extended to include not only the economic order quantity but also the carbon intensity parameter (Battini et al., 2014).

#### **4.3. Decision Support and Pareto Analysis**

In multi-objective optimization problems, there is no single best solution; instead, a set of Pareto-optimal solutions is obtained. Decision-makers choose solutions according to their strategic priorities. At this point, big data-driven decision support systems (DSS) play a critical role in visualizing Pareto curves and performing scenario analyses.

Ivanov and Dolgui (2021) demonstrated that network performance and decision quality can be improved by analyzing alternative scenarios using data-driven simulation and digital twin approaches. Such systems make it possible to evaluate how cost and operational indicators change under different scenarios, and they also indirectly provide a basis for analyzing sustainability impacts. From this perspective, the cost–time–carbon balance evolves beyond a purely mathematical optimization problem into a strategic decision problem. Big data infrastructure and smart systems facilitate the real-time monitoring and management of this balance.

Multi-objective optimization models generate alternative decisions within a cost-time-carbon framework and offer Pareto-efficient solution sets. However, to align these solutions with corporate sustainability goals, they need to be systematically measured and evaluated using performance indicators. Converting optimization outputs into metrics, such as carbon intensity, energy efficiency, and operational agility, forms the basis for the transition from analytical solution generation to strategic decision management. Therefore, multi-objective optimization generates real value when considered with sustainability performance measurements and decision intelligence mechanisms. In the next section, we will discuss in detail how the optimization results are measured, converted into traceable KPIs, and integrated into strategic management processes through decision support systems.

## **5. Sustainability Performance Measurement and Decision Intelligence**

In sustainable logistics systems, optimization models generate alternative decisions; however, for these alternatives to gain corporate value, they need to be systematically measured, monitored, and integrated into management processes. Therefore, sustainable performance measurement and decision intelligence form the management layer of a big data-driven green logistics architecture.

The smart systems discussed in previous chapters provide data visibility and multi-objective optimization models that generate Pareto-efficient solutions within a cost-time-carbon framework. This section examines how these solutions are translated into measurable performance indicators and integrated into strategic decision-making processes.

### **5.1. Performance Measurement Framework in Sustainable Logistics**

Measuring sustainable performance requires a holistic approach that includes environmental and social dimensions, as well as economic indicators. Seuring and Müller (2008) emphasized that systematically monitoring and reporting environmental performance in sustainable supply chain management is a key theme in the field.

The key performance indicators of green logistics include carbon intensity (CO<sub>2</sub>/delivery or ton-km), energy efficiency ratio, and empty kilometer percentage. In addition, indicators such as emissions per delivery and warehouse energy consumption are also used to assess operational sustainability. These indicators enable the conversion of multi-objective optimization outputs into measurable performance metrics. In green logistics practices, environmental performance must be embedded in planning, monitoring, and control processes. In this context, performance measurement evolves beyond a static reporting tool and becomes a dynamic management mechanism.

## 5.2. Key Sustainability KPI Framework

To integrate the outputs of multi-objective optimization into the performance system, they need to be translated into measurable and operational performance indicators. The key KPIs of green logistics are outlined below.

The technical management of sustainable logistics performance requires a quantitative calculation of carbon emissions. In practice, a widely adopted approach involves multiplying the fuel consumption by the corresponding emission factor as follows:

$$CO_2 = \text{Fuel Consumption} \times \text{Emission Factor}$$

This method is based on the standard calculation approach recommended by the Greenhouse Gas Protocol (2011). For ton-km-based comparisons, the carbon intensity can be expressed as follows:

$$\text{Carbon Intensity (CI)} = \frac{\text{Total } CO_2 \text{ Emissions}}{\text{Transported Load} \times \text{Distance}}$$

$$\text{Energy Efficiency Ratio (EER)} = \frac{\text{Transport Work (ton - km)}}{\text{Total Energy Consumption}}$$

$$\text{Empty Kilometer Ratio (EKR)} = \frac{\text{Empty Distance}}{\text{Total Distance}}$$

$$\text{Emission Reduction Rate (\%)} = \frac{\text{Emissions}_{reference} - \text{Emissions}_{actual}}{\text{Emissions}_{reference}}$$

These indicators allow for the comparison of the environmental performance of different routes and network alternatives. Calculating Scope 1, Scope 2, and Scope 3 emissions requires the integration of fleet, energy, and supplier data (Greenhouse Gas Protocol, 2013).

## 5.3. The Connection Between ESG and Corporate Reporting

Sustainable logistics performance is no longer just an operational evaluation area; it is increasingly becoming a part of corporate reporting in line with investor expectations and the regulatory frameworks. Within the ESG framework, companies are moving towards providing transparency regarding carbon emissions and energy performance.

Big data infrastructures enable the integration of different operational data sources, allowing real-time monitoring, analysis, and reporting of carbon and energy indicators. This ensures that sustainable logistics performance is not limited to historical reports; environmental outputs can be dynamically tracked and integrated into operational decisions (Shen et al., 2024; Liao & Guo, 2025).

Studies examining the role of big data analytics in the context of sustainable production and supply chains reveal that data-driven decision-making contributes to improved environmental performance by increasing transparency and traceability (Do et al., 2025). Similarly, it has been emphasized that operational data integration provides critical infrastructure for the systematic measurement and reporting of carbon and energy indicators (Khan et al., 2025). These findings demonstrate that sustainable performance measurement is a comprehensive management process based on digital infrastructure, analytical capabilities, and data integration, in addition to reporting activities.

#### **5.4. Decision Intelligence: From Optimization to Strategy**

Decision intelligence represents an integrated framework that combines data analytics, optimization outputs, and managerial decision-making processes into a unified structure. Building upon traditional decision support systems, this approach goes beyond merely presenting data by enabling comparative evaluation of alternative operational scenarios. By integrating predictive analytics, simulation, and optimization models, decision intelligence strengthens the link between analytical outputs and strategic managerial action (Davenport, 2018).

Scenario-based modeling has long been recognized as a mechanism for enhancing decision robustness under uncertainty (Klibi et al., 2010; Dolgui et al., 2018). Through the systematic comparison of alternative configurations, managers can evaluate the trade-offs between cost, service level, resilience, and sustainability dimensions. Within this analytical paradigm, digital twin technologies offer a simulation environment in which operational and environmental indicators can be analyzed simultaneously. Ivanov and Dolgui (2021) demonstrated that digital supply chain twins enable the structured evaluation of alternative scenarios by associating real-time data with simulation-based optimization, thereby improving decision quality.

The key is that the transition from optimization to strategy occurs through the management of trade-offs. The literature on green logistics and pollution steering problems shows that economic and environmental goals often move in opposite directions, requiring conscious balancing mechanisms (Bektas & Laporte, 2011; Demir et al., 2014). For example, a limited increase in transportation costs can lead to a disproportionately higher reduction in

carbon emissions. This situation indicates a nonlinear relationship between cost and environmental impact. A comparative analysis of such scenarios provides a quantitative basis for managing the cost-time-carbon balance.

From a strategic perspective, decision intelligence transforms Pareto-efficient solutions into actionable governance tools. Instead of treating optimization outputs as static end results, organizations can continuously monitor, evaluate, and recalibrate their operational structures in response to changes in environmental, regulatory, and market conditions. In this context, big data infrastructure and smart systems bridge the gap between analytical rigor and strategic intent by enabling adaptive and real-time management of sustainability-focused logistics networks..

### **5.5. Feedback Loop and Continuous Improvement**

Sustainable logistics performance is dynamic and requires continuous monitoring. In big data-driven systems, a feedback mechanism is formed between performance measurement and optimization: operational data are collected, the optimization model generates solutions, environmental and economic KPIs are calculated, and model parameters are updated in line with the obtained results.

Wamba et al. (2020) and Dubey et al. (2021) demonstrate that big data analytics capabilities are associated with supply chain agility and improved performance. This agility can support sustainability management at the operational excellence level by enabling the dynamic monitoring of performance indicators and the development of data-driven strategies (Singh & El-Kassar, 2019; Bag et al., 2020).

Within this framework, sustainable performance measurement and decision intelligence are positioned as managerial complements to multi-objective optimization models. When smart systems providing data visibility, analytical models, and KPI-based monitoring mechanisms work together, sustainability ceases to be an operational constraint and transforms into a measurable and strategically manageable performance dimension.

## **6. Challenges in Implementing Big Data-Enabled Green Logistics**

Although big data-driven green logistics systems theoretically have the potential to optimize the cost-time-carbon balance, they present significant technical, organizational, and managerial challenges during implementation. These challenges are multifaceted and range from data infrastructure to cultural transformation issues.

### **6.1. Data Quality, Integration, and Standardization Issues**

Big data-driven sustainability management requires the integration of heterogeneous data from diverse sources, including telematics data, IoT

sensor outputs, Enterprise Resource Planning (ERP) systems, traffic flows, and emission factors. However, these data are generated in different formats with varying time resolutions and accuracy levels. Data quality problems (missing data, erroneous sensor outputs, and delayed transmission) directly impact the reliability of sustainability performance calculations.

The sustainable supply chain literature emphasizes that information transparency and traceability are critical to environmental performance (Seuring & Müller, 2008). However, in practice, the lack of data standardization creates significant methodological uncertainties, particularly in Scope 3 emission calculations (Greenhouse Gas Protocol, 2013).

### **6.2. Analytical Competence and Organizational Readiness**

Establishing a big data infrastructure alone is insufficient; analytical capabilities also need to be developed. Studies showing that big data analytics capacity has an impact on supply chain agility and performance reveal that technological investments must be supported by organizational capabilities (Wamba et al., 2020; Dubey et al., 2021). This case is twofold in green logistics: analytical models must accurately incorporate sustainability parameters, and decision-makers must be able to interpret multidimensional outcomes, such as the carbon-cost balance. Organizational resistance, silo structures, and insufficient alignment of sustainability goals with operational goals can hinder a big data-driven green transformation.

### **6.3. Complexity of Multi-Objective Optimization**

The optimization of cost, service level, and carbon emissions simultaneously creates mathematically complex problems. The literature on the Green Vehicle Routing Problem shows that emissions and fuel consumption depend on speed, load, and route structure (Bektaş & Laporte, 2011; Demir et al., 2014). This prolongs the model solution time and creates computational difficulties, particularly in real-time applications.

Dynamic optimization systems require high processing power and advanced algorithmic capabilities. Integrating real-time data streams into an optimization model presents a technical challenge in terms of system scalability.

### **6.4. Data Security and Ethical Aspects**

The use of big data systems in logistics networks contains sensitive information, such as vehicle location data, customer data, and operational trade secrets. Cybersecurity risks, data manipulation, and privacy breaches can undermine the reliability of sustainable systems. Furthermore, the transparency and explainability of decision-making algorithms are gaining importance, particularly in the context of ESG reporting. Corporate sustainability performance needs to be scrutinized by investors and regulators.

### 6.5. Economic and Regulatory Uncertainties

The variation in carbon pricing mechanisms and regulatory frameworks from country to country increases the uncertainty surrounding carbon costs that are integrated into optimization models. This can affect the long-term accuracy of the strategic decisions.

Dekker et al. (2012) emphasize that green logistics practices are influenced by policy and regulatory contexts as well as operational aspects. Therefore, big data-driven green logistics involves a technical transformation, along with a process of institutional and regulatory compliance.

### 7. Future Directions: Toward Carbon-Neutral and Autonomous Logistics Networks

Future research and application trends for big data-driven green logistics systems are shaped by carbon-neutral goals, autonomous systems, and network-level adaptive decision architectures. This transformation requires the integration of Industry 4.0 technologies, electric mobility, digital twins, and system-level carbon accounting.

*Carbon-Neutral Network Design and Science-Based Targets:* In line with global climate policies and net-zero targets, logistics networks need to be redesigned not only for emission reduction but also for carbon neutrality (Chen et al., 2024). The IPCC (2022) reports emphasize the necessity of deep decarbonization of the transportation sector. This requires integrated optimization models in logistics network design that include energy source transformation (electric and hydrogen fuel cell vehicles), warehouse energy infrastructure, and distribution density.

*Industry 4.0 and Sustainable Logistics Integration:* Industry 4.0 technologies (IoT, cyber-physical systems, artificial intelligence) enable real-time monitoring of sustainable performance. The integration of big data analytics, blockchain, and sensor networks enhances carbon traceability and process transparency. Future logistics systems will rely on integrated digital platforms that simultaneously optimize not only the cost and service level but also parameters such as carbon intensity and energy flexibility.

*Autonomous and Semi-Autonomous Transportation Systems:* Autonomous vehicle technologies and platooning systems have the potential to reduce fuel consumption and emissions. The widespread adoption of electric and autonomous heavy-duty systems can increase operational efficiency while lowering carbon intensity. However, the energy infrastructure, battery production, and lifecycle emissions of these systems should also be considered. The digital supply chain twin approach (Ivanov & Dolgui, 2021) allows for the simulation of the network effects of autonomous decision-making systems. In the future, decision intelligence systems may evolve from human-assisted

decision-making structures to semi-autonomous and carbon-threshold-sensitive decision-making mechanisms.

*Learning and Adaptive Carbon Awareness Networks:* The “viable supply chain” model developed by Ivanov (2022) aims to ensure the long-term functionality of supply chains by integrating agility, resilience, and sustainability from a holistic network perspective. This framework emphasizes the role of digital technologies and data-driven modelling approaches in the adaptive management of network performance. Big data-driven logistics networks are evolving into systems that can monitor performance indicators and dynamically update their operational parameters.

Accordingly, future logistics systems will have three fundamental characteristics:

- Carbon-aware optimization,
- Autonomous or semi-autonomous decision-making mechanisms,
- Continuously learning and adapting network structures.

The transition to carbon-neutral and autonomous logistics networks requires a holistic transformation encompassing not only technological innovations but also organizational structures, governance mechanisms, and regulatory compliance processes.

### **Conclusion**

This book chapter comprehensively addresses the conceptual foundations, technical infrastructure, analytical layers, and impacts on the sustainability performance of a big data-driven green logistics approach. The global climate crisis, net-zero targets, and ESG-based regulatory pressures are forcing the logistics sector to restructure not only in terms of operational efficiency but also in terms of carbon intensity and energy performance. In this context, big data is positioned as a strategic enabler that makes environmental sustainability possible in logistics systems.

Literature findings show that big data analytics capabilities have significant and positive impacts on supply chain agility, operational performance and environmental outputs (Wamba et al., 2020; Dubey et al., 2021). However, this impact arises not only from the increase in data volume but also in conjunction with data governance, analytical capabilities, multi-objective optimization models, and decision support systems. Therefore, big data infrastructure is not a standalone solution in sustainable logistics; it is a system component that generates value when integrated with analytical and managerial mechanisms.

The multi-objective optimization models discussed in this study mathematically model the cost-time-carbon balance and generate Pareto-efficient solution sets. However, the real value emerges when these solutions are measured using sustainability KPIs and transformed into strategic governance tools within the framework of decision intelligence. Indicators such as carbon intensity, energy efficiency, empty mileage rate, and emission reduction rate enable the integration of optimization outputs into management decision-making processes.

Big data-driven smart systems create three fundamental impact mechanisms in logistics networks: (i) real-time visibility and monitoring, (ii) prediction and multi-objective optimization, and (iii) continuous improvement through dynamic measurement and feedback on sustainability performance. This structure transforms sustainability from a static reporting activity into a data-driven management system that places it at the center of operational decisions.

From a future perspective, carbon-aware, learning, and adaptive logistics networks are noteworthy. Digital twins, autonomous decision-making mechanisms, and real-time carbon optimization systems will be decisive in achieving carbon neutrality targets in the logistics sector. However, significant challenges remain in areas such as data quality, methodological standardization, organizational transformation, and regulatory compliance issues. Therefore, the big data-driven green logistics transformation should be considered not merely a technical modernization process, but a strategic, corporate, and managerial paradigm shift.

In conclusion, the big data-driven green logistics approach makes the cost-time-carbon trade-off manageable through the integration of data infrastructure, analytical capabilities, multi-objective optimization, and sustainable performance measurement, transforming logistics systems into strategically oriented structures that comply with environmental responsibility. This transformation forms the foundation of the carbon-aware and data-driven logistics networks of the future.

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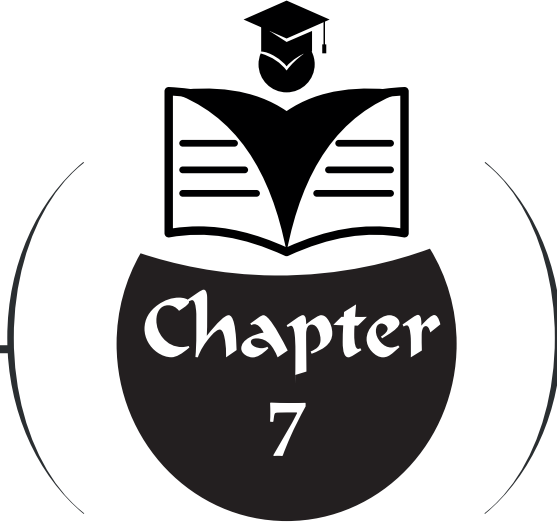
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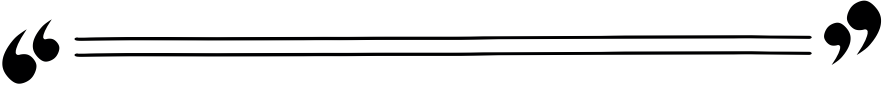
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**SUSTAINABLE TRANSPORTATION  
INFRASTRUCTURE IN GREEN LOGISTICS:  
HIGHWAY–RAILWAY SYSTEMS AND PAVEMENT  
MATERIALS**



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## INTRODUCTION

In contemporary logistics systems, transportation networks constitute the fundamental backbone ensuring the continuity of global trade; however, they also occupy a central position in sustainability debates due to transportation-related energy consumption and greenhouse gas emissions (Schipper, Marie-Lilliu, & Gorham, 2000). The increasing volume of freight transport not only intensifies transport operations but also expands the construction, maintenance, and operation of the physical infrastructure that enables these activities (IPCC, 2021). Consequently, the environmental impacts of logistics activities have acquired a multi-layered and complex character. Within this context, green logistics should be regarded not merely as a pursuit of “more efficient transportation,” but as a comprehensive paradigm aiming at the transition toward a low-carbon logistics regime through the planning, design, and life-cycle management of infrastructure systems.

The green logistics approach is shaped by objectives such as enhancing resource efficiency, reducing emissions, and controlling environmental impacts. Nevertheless, achieving these objectives cannot be limited solely to vehicle technologies, fuel types, or operational optimization. Indeed, the environmental performance of transport systems is directly related to infrastructure design parameters, the characteristics of the materials used, maintenance and rehabilitation strategies, and performance deterioration occurring over the service life. Therefore, sustainable transportation systems must not only benefit from the environmental advantages of different transport modes but also require infrastructure to be planned and managed according to engineering-based sustainability principles throughout its life cycle.

Transportation infrastructure represents a complex system consisting of highway and railway networks, port connections, logistics centers, and the structural components supporting them. The sustainability of this system should be evaluated not only in terms of capacity and accessibility, but also from a life-cycle perspective extending from material extraction and production to construction, maintenance and rehabilitation, and end-of-life management. Within this framework, pavement systems constitute a particularly critical component, as they are exposed to heavy vehicle traffic along logistics corridors, require substantial quantities of raw materials and energy inputs, and may influence transport continuity due to maintenance activities. The use of reclaimed asphalt pavement (RAP) in asphalt layers, the incorporation of recycled aggregates in granular layers, the improvement of bituminous binders through sustainable additives, and the strategic management of maintenance processes emerge as engineering-based tools that jointly enhance the environmental and functional performance of infrastructure in line with green logistics objectives.

In this chapter, the sustainable transportation infrastructure approach within the scope of green logistics is examined with specific emphasis on highway and railway transport systems, and these two modes are compared in terms of their environmental performance and infrastructure requirements in the context of green logistics. Subsequently, sustainability in pavement systems is systematically discussed through life-cycle cost approaches, recycling-based material strategies, binder modification techniques, and the effects of maintenance processes on green logistics performance. The main objective of this chapter is to make visible the relationship between sustainable transportation systems and infrastructure engineering, and to situate the role of pavement materials and management strategies—often treated as secondary yet in fact decisive within the green logistics literature—within an academic framework from the perspective of civil engineering.

Accordingly, this chapter argues that green logistics performance can be explained not only through “transport operations” but also through the triad of “infrastructure–materials–maintenance,” and positions the discussion explicitly within the domain of civil engineering.

### **1. Overview of Transportation Infrastructure in Green Logistics**

Transportation infrastructure constitutes the physical foundation of logistics systems and represents one of the most critical components ensuring the continuity of freight flows. Within the framework of the green logistics approach, transportation infrastructure should be evaluated not only in terms of transport capacity and economic efficiency, but also with respect to environmental sustainability, energy consumption, and carbon emissions. In this context, the planning and design of infrastructure systems must be reconsidered in alignment with the fundamental objectives of green logistics.

Conventional transportation infrastructures have generally been designed with a primary focus on short-term cost and capacity considerations, while environmental impacts have often remained of secondary importance. However, increasing global warming, climate change, and the limited availability of natural resources necessitate that the long-term environmental effects of transportation infrastructure be taken into account. Accordingly, transportation infrastructure within green logistics is assessed based on criteria such as low-carbon design, energy efficiency, and the use of environmentally friendly materials.

Highway and railway infrastructures represent the most widely used transport modes in green logistics systems. While road transport stands out in terms of flexibility and accessibility, railway transport offers advantages in sustainability due to its lower energy consumption and emission levels. Therefore, in green logistics applications, the type of transportation

infrastructure and the integration of different infrastructure systems play a crucial role.

From a civil engineering perspective, the sustainability of transportation infrastructure is directly related to the design life of the facility, maintenance requirements, and the characteristics of construction and pavement materials. (U.S. Federal Highway Administration [FHWA], 2017). Infrastructure systems constructed with long-lasting, low-maintenance, and environmentally friendly materials make a significant contribution to reducing the environmental impacts of logistics activities.

## **2. Transportation Systems in Green Logistics**

Within the scope of green logistics, transportation systems should be considered not only as organized transport operations but also together with the infrastructure systems that enable these operations. The environmental impacts of transportation systems vary depending on the transport mode used, infrastructure characteristics, and operational conditions. Therefore, in the green logistics approach, transportation systems must be addressed from a holistic perspective and restructured in line with environmental sustainability objectives.

Road and railway transport are the two most widely used transport modes in freight transportation and exhibit different advantages and limitations in green logistics applications. While road transport is characterized by flexibility and accessibility, railway transport provides environmental advantages in terms of energy efficiency and lower emission levels. In this context, the comparison of the environmental performance of these two transport modes and the development of appropriate integration strategies are of critical importance for the establishment of sustainable transportation systems.

The sustainability of transportation systems is not limited to the selection of transport modes, but is directly associated with the design and operation of the supporting infrastructure. From a civil engineering standpoint, the structural characteristics of road and rail infrastructures, the materials employed, and maintenance strategies play a decisive role in determining the environmental impacts of transport activities. Hence, transportation systems in green logistics should be regarded as multidimensional structures in which engineering design and environmental performance are addressed simultaneously.

This section examines highway and railway transport systems within the scope of green logistics under separate headings, compares their environmental and technical characteristics, and discusses infrastructure-based approaches for the development of sustainable transportation systems.

## 2.1. Road Transportation in Green Logistics

Road transportation continues to be the most widely used transport mode in logistics systems due to its accessibility and operational flexibility. However, compared to other transport modes, road transport generates higher levels of energy consumption and greenhouse gas emissions, thereby constituting a significant challenge in terms of environmental sustainability (Schipper, Marie-Lilliu, & Gorham, 2000). For this reason, within the framework of green logistics, road transport should be reassessed not only in terms of transport operations but also with respect to infrastructure design and operational performance.

Within green logistics, the primary objective of road infrastructure is to ensure the continuity of transport activities while reducing their environmental impacts. In this regard, engineering parameters such as road geometry, intersection design, gradient values, and pavement type directly influence vehicle fuel consumption and emission levels. In particular, pavements with smooth surface characteristics and low rolling resistance play an important role in reducing the energy consumption of heavy vehicles.

The interaction between pavement surface characteristics and vehicle fuel efficiency is primarily governed by rolling resistance, which accounts for a significant portion of the energy required to propel heavy-duty vehicles. From a mechanical standpoint, rolling resistance is induced by the hysteretic energy loss resulting from the continuous deformation of tires as they traverse the pavement surface. Research indicates that pavement roughness and macrotexture directly influence the rolling resistance coefficient; a deterioration in pavement condition can lead to an increase in fuel consumption ranging from 2% to 5% for heavy vehicles (Huang, Bird, & Heidrich, 2009). By optimizing pavement design through the use of high-performance materials and maintaining a low international roughness index (IRI), infrastructure engineering can significantly reduce the cumulative carbon emissions of logistics operations, effectively transforming the pavement into a functional component of the green energy-saving strategy (Santero, Masanet, & Horvath, 2011).

In addition to infrastructure, traffic management and operating conditions are also decisive in reducing the environmental impacts of road transportation. Intelligent Transportation Systems (ITS) contribute to lowering fuel consumption and emissions by reducing traffic congestion and minimizing stop-and-go conditions. The effective implementation of these systems requires the integration of digital equipment and sensor-based monitoring systems compatible with the physical infrastructure.

Furthermore, the integration of Intelligent Transportation Systems (ITS) and IoT-based structural health monitoring sensors allows for the real-time

tracking of pavement surface degradation and its correlated impact on vehicle rolling resistance. Such data-driven infrastructure management enables predictive maintenance strategies that prevent excessive fuel consumption before surface irregularities reach critical levels, thus creating a synergistic link between digital technologies and sustainable pavement engineering within the green logistics framework.

Furthermore, the life-cycle approach constitutes a significant tool in the evaluation of road infrastructure within green logistics. Road projects should be assessed not only in terms of construction-stage costs, but also with regard to the environmental impacts generated throughout their service life, including maintenance and rehabilitation. Pavement systems characterized by long service life and low maintenance requirements offer advantages both economically and in terms of environmental sustainability. This perspective necessitates that road infrastructure be considered not merely as a transport platform but as an integral component of sustainable logistics systems.

## **2.2. Railway Transportation in Green Logistics**

Railway transportation is regarded as an important alternative transport mode in green logistics due to its high transport capacity and energy efficiency. Particularly in long-distance freight transport, the lower energy consumption and greenhouse gas emissions per unit of transport make rail systems environmentally advantageous. For this reason, railway transportation is widely recognized as a system with a lower carbon footprint compared to road transportation.

From the green logistics perspective, the environmental performance of railway transportation depends not only on transport operations but also on the design and operation of infrastructure systems. The geometric design of railways, line capacity, and signaling systems significantly affect energy consumption and operational efficiency. Moreover, the level of electrification and the type of energy sources used directly influence the environmental impacts of railway transport. Electrified rail lines powered by renewable energy sources provide considerable potential for reducing carbon emissions.

The sustainability of railway infrastructure is also associated with the materials used in construction and with maintenance and rehabilitation processes. The durability of structural components such as rails, sleepers, and ballast layers extends service life and yields both economic and environmental benefits. Long-lasting and low-maintenance railway infrastructures contribute to reducing environmental impacts over the life cycle of the system. In this context, the adoption of life-cycle assessment approaches in railway design supports the development of an engineering perspective consistent with green logistics objectives.

Another key factor enhancing the effectiveness of railway transportation in green logistics is its integration with other transport modes. Railway infrastructures planned in connection with ports, logistics centers, and road networks promote the development of intermodal transportation systems. Such integrated transport structures reduce dependence on road transport and contribute to emission reductions in freight transport. Accordingly, railway transportation should be regarded not only as an independent transport mode but also as a fundamental component of multimodal logistics networks (Stripple & Uppenberg, 2010).

### **2.3. Comparison of Road and Railway Transportation (from a Green Logistics Perspective)**

Within the green logistics framework, road and railway transportation exhibit different characteristics in terms of environmental performance, energy efficiency, and infrastructure requirements. Road transportation plays a significant role in logistics systems due to its flexible routing and door-to-door service capability, whereas railway transportation provides sustainability advantages through higher transport capacity and lower unit energy consumption. The environmental impacts of these two transport modes should therefore be evaluated together in relation to the infrastructure systems and operational conditions employed.

From the standpoint of energy consumption, railway transportation requires less energy per ton-kilometer than road transportation. This makes rail transport a more environmentally appropriate option, particularly for long-distance freight transport. In road transportation, factors such as vehicle type, traffic conditions, and road geometry directly affect energy use. Consequently, the environmental performance of road transport is closely linked to infrastructure design and traffic management.

Comparisons based on carbon emissions indicate that railway transportation is more advantageous in terms of greenhouse gas emissions. Nevertheless, road transportation remains indispensable for logistics systems due to the operational flexibility it provides in short-distance and dispersed freight movements. This situation highlights the importance of integration-based solutions rather than systems relying on a single transport mode in green logistics applications.

In terms of infrastructure investments, railway systems require higher initial capital costs than road infrastructures; however, their long service life and high transport capacity enable them to offer long-term environmental and economic benefits. Road infrastructures, by contrast, are characterized by lower initial investment costs and shorter construction periods, but their long-term environmental impacts become more pronounced due to intensive maintenance needs and heavy traffic loads.

In the context of Türkiye, freight transport is predominantly road-based, although policies aimed at increasing the share of railway transport have been developed in recent years. In this transformation process, integrated transport networks in which road and railway infrastructures are jointly planned are considered important tools for achieving green logistics objectives. In particular, the planning of logistics centers with direct railway connections represents a structural transformation that can reduce the environmental impacts of freight transportation.

In conclusion, road and railway transportation should not be regarded as alternatives but as complementary components within green logistics systems. The development of integrated infrastructure approaches that exploit the environmental and technical advantages of both modes is essential for establishing sustainable transportation systems. Such an approach not only contributes to reducing the environmental impacts of logistics activities but also facilitates the effective implementation of sustainability principles in long-term infrastructure planning. Road and railway transportation are comparatively evaluated from a green logistics perspective in Table 7.1.

**Table 7.1.** *Comparative Assessment of Road and Railway Freight Transport from a Green Logistics Perspective*

<b>Comparison Criterion</b>	<b>Road Transportation</b>	<b>Railway Transportation</b>
Energy consumption (per unit of freight)	Relatively high	Relatively low
Carbon emission level	High	Low
Transport capacity	Medium	High
Operational flexibility	High (door-to-door service)	Medium (dependent on stations and rail lines)
Initial infrastructure investment cost	Relatively low	Relatively high
Infrastructure maintenance requirement	Frequent and costly	Less frequent and longer service life
Suitability for long-distance transport	Medium	High
Suitability for short-distance transport	High	Low
Integration of renewable energy sources	Limited (indirect)	High (through electrification)
Suitability for intermodal transport	High	High
Role in green logistics	Flexible complementary mode	Main backbone transport mode

### 3. Sustainability in Pavement Systems

Pavement systems represent one of the most critical infrastructure components forming the physical backbone of logistics systems. The sustainability of this infrastructure cannot be explained solely in terms of transport capacity or initial construction cost; rather, it requires a comprehensive life-cycle perspective extending from raw material extraction and production to construction, maintenance and rehabilitation, and end-of-life management. Accordingly, the sustainability of pavement materials should be addressed in a manner that simultaneously considers the reduction of environmental impacts and the preservation of engineering performance and durability.

Conventional road construction practices involve high levels of natural aggregate consumption and energy-intensive processes, thereby contributing significantly to the carbon footprint of highway infrastructures. In addition, the frequent maintenance and rehabilitation requirements along logistics corridors exposed to heavy vehicle traffic increase both economic costs and environmental burdens. Within this context, the primary objective of sustainable pavement design is to develop solutions that consume fewer natural resources, generate lower energy and emission impacts, and provide longer service life with reduced maintenance requirements (Stripple, 2001).

Recycling constitutes one of the most effective tools for achieving sustainability objectives in pavement systems. The use of reclaimed asphalt pavement (RAP) in asphalt layers reduces the demand for natural aggregates and virgin binder, thereby enhancing resource efficiency. Similarly, the utilization of recycled aggregates in base and subbase layers contributes to both waste management and material sustainability through the valorization of construction and demolition waste. However, the widespread adoption of recycled materials requires that performance, durability, climatic suitability, and quality control processes be addressed simultaneously.

This section systematically examines pavement components within a recycling-oriented framework, encompassing asphalt layers, granular layers, stabilization applications, and maintenance and operational effects. The aim is to propose engineering-based and applicable material strategies that support circular economy principles in road infrastructure in line with green logistics objectives.

#### 3.1. Sustainable Pavement Materials within a Life-Cycle Cost Framework

In sustainable pavement design, long-term engineering costs must be considered alongside environmental performance. Evaluating a pavement solution solely on the basis of initial construction cost may lead to misleading

conclusions, particularly along logistics corridors subjected to heavy traffic loads. Therefore, sustainable pavement materials should be assessed within a framework that incorporates initial investment cost, maintenance and rehabilitation requirements, service life, and performance deterioration during operation.

From an engineering economics perspective, long-lasting and durable pavement systems may entail higher initial construction costs; however, they can reduce total life-cycle costs by requiring less frequent maintenance and rehabilitation over their service life (Santero, Masanet, & Horvath, 2011). In pavement systems incorporating recycled materials, the reduction in the use of natural aggregates and virgin binders lowers material costs while simultaneously decreasing energy consumption associated with production processes. This situation enables environmental gains and engineering cost savings to be achieved concurrently.

In logistics infrastructures, frequent pavement maintenance leads not only to direct repair costs but also to indirect effects such as increased transport times and capacity losses. Accordingly, sustainable pavement materials should be regarded as structural elements that support the continuity of logistics systems by extending maintenance intervals and increasing service life. This perspective integrates sustainability not merely as an environmental objective but also as a component of infrastructure performance and operational efficiency.

In conclusion, the use of sustainable materials in pavement systems should not be defined solely by recycled content; rather, it should be evaluated together with long-term performance, maintenance requirements, and impacts on logistics operations. Within this context, the life-cycle cost approach emerges as a key decision-support tool for engineering-based planning of road infrastructures in line with green logistics objectives.

### **3.2. Use of Reclaimed Materials in Asphalt Layers**

One of the most widespread and effective applications of sustainability in pavement engineering is the use of reclaimed materials in asphalt layers. Reclaimed asphalt pavement (RAP) is obtained by milling or removing existing asphalt layers and reprocessing the material for reuse in new asphalt mixtures (Shen, Amirkhanian, & Carpenter, 2007). This practice reduces the demand for virgin aggregates and binders, thereby improving resource limiting waste generation. In this respect, RAP utilization represents a practical manifestation of circular economy principles in pavement engineering.

The proportion of RAP incorporated into asphalt mixtures is a critical parameter that directly influences mechanical performance. Mixtures containing low RAP contents may exhibit performance comparable to

conventional hot-mix asphalts; however, as RAP content increases, mixture stiffness tends to rise and susceptibility to low-temperature cracking may become more pronounced. For this reason, the use of rejuvenating agents and performance-based mix design methods becomes increasingly important in mixtures with high RAP contents. Through such approaches, environmental benefits can be preserved while ensuring compliance with structural performance requirements.

The influence of reclaimed materials on long-term pavement behavior extends beyond the asphalt layer itself and affects overall pavement performance. Criteria such as fatigue resistance, permanent deformation, and moisture damage resistance constitute key indicators in the evaluation of RAP-containing mixtures. Previous studies have demonstrated that, when appropriate mix design procedures and quality control measures are implemented, asphalt mixtures incorporating RAP can achieve performance levels comparable to, or in some cases superior to, those of conventional mixtures. These findings indicate that recycling practices are not only environmentally advantageous but also technically feasible from an engineering standpoint.

In the context of Türkiye, academic studies on the use of reclaimed materials in asphalt layers have increased notably in recent years. Experimental investigations in the domestic literature report that RAP-containing mixtures exhibit acceptable Marshall stability, stiffness modulus, and moisture damage resistance (Güler, 2018). Nevertheless, these studies also emphasize that binder properties must be carefully controlled in high-RAP mixtures and that mixture performance may vary depending on climatic conditions. Such findings suggest that technical specifications and mix design methodologies should be adapted to facilitate the wider implementation of recycled asphalt applications under national conditions.

From a green logistics perspective, the significance of reclaimed material use in asphalt layers extends beyond material savings. Reduced consumption of virgin raw materials, lower production energy demand, and extended maintenance intervals along logistics corridors collectively enhance the continuity of transport operations. Moreover, the widespread adoption of recycled materials contributes to a reduction in emissions associated with pavement construction and rehabilitation, thereby lowering the overall carbon footprint of logistics systems. In this sense, RAP and related applications constitute infrastructure-based solutions that are directly aligned with green logistics objectives.

In conclusion, the use of reclaimed materials in asphalt layers represents one of the most mature and implementable approaches to achieving sustainability in pavement systems. However, the success of such applications

depends on accurate characterization of reclaimed materials, performance-based mix design, and effective quality control during construction. When these conditions are satisfied, pavements incorporating recycled materials can become fundamental components of green logistics infrastructure in terms of both engineering performance and environmental benefit.

### **3.3. Use of Recycled Materials in Granular Base and Subbase Layers**

Granular base and subbase layers play a crucial structural role in pavement systems by ensuring the safe transfer of loads to the underlying soil and directly influencing pavement performance. The extensive use of natural aggregates in these layers leads to substantial consumption of natural resources, thereby making the incorporation of recycled materials a priority area in sustainable pavement engineering.

Recycled materials used in granular layers are commonly derived from construction and demolition waste, reclaimed asphalt aggregates, and selected industrial by-products. When these materials satisfy appropriate gradation and mechanical property requirements, they can effectively replace natural aggregates in base and subbase layers. Previous research has shown that recycled aggregates can exhibit acceptable bearing capacity and drainage characteristics when properly processed and designed.

The engineering performance of recycled materials in granular layers is typically evaluated with respect to parameters such as bearing capacity, resistance to permanent deformation, and freeze–thaw durability. Crushed concrete aggregates, in particular, tend to display enhanced shear strength due to their angular particle shape, which positively influences load-bearing behavior. However, their relatively high water absorption capacity necessitates careful attention to drainage design and frost resistance.

Studies conducted under Turkish conditions similarly indicate that recycled concrete and asphalt aggregates used in base layers yield California Bearing Ratio (CBR), compaction behavior, and drainage properties comparable to those of conventional materials. Nevertheless, material variability remains a critical issue, underscoring the importance of stringent quality control procedures in such applications (Akbulut & Aslantas, 2005).

The contribution of recycled materials in granular layers to green logistics is not limited to reduced natural resource consumption. By decreasing the need for quarrying and transportation of virgin aggregates, these practices also reduce indirect emissions associated with material supply chains. Furthermore, the integration of recycled materials into road construction links pavement engineering with waste management systems, thereby fostering a more circular and resource-efficient logistics structure.

In summary, the use of recycled materials in granular base and subbase

layers offers substantial potential for enhancing sustainability in pavement systems. The effective realization of this potential depends on proper material characterization, sound mix design principles, and systematic quality control during construction. Under these conditions, recycled granular layers can serve as reliable components of green logistics infrastructure in terms of both environmental and engineering performance.

### **3.4. Improvement of Bituminous Binders through Sustainable Additives**

The engineering performance of bituminous binders plays a decisive role in determining pavement service life and maintenance requirements. Limitations such as permanent deformation at high temperatures, cracking at low temperatures, and aging-related deterioration represent fundamental challenges for conventional binders. Although polymer modification has traditionally been employed to address these issues, the production of such modifiers may impose additional environmental burdens. Consequently, the use of recycled and alternative additives has gained increasing attention within the framework of sustainable pavement engineering.

Recent studies demonstrate that waste tire rubber, recycled plastics, and various mineral-based additives can significantly improve the rheological properties of bituminous binders (Yao et al., 2013). These additives enhance resistance to high-temperature deformation, reduce temperature susceptibility, and retard aging processes. At the same time, their use enables the valorization of waste materials, thereby aligning binder modification practices with circular economy principles. Binder modification thus evolves into an engineering application that simultaneously delivers performance improvement and environmental benefit (Shen, Amirkhanian, & Carpenter, 2007).

Another important application involves the reactivation of aged binders obtained from reclaimed asphalt pavement. In mixtures containing RAP, the hardened binder phase may increase cracking susceptibility. Rejuvenating agents are therefore employed to restore viscosity and elasticity characteristics. By facilitating higher proportions of reclaimed materials, rejuvenators reduce the demand for virgin binder and decrease the environmental footprint of asphalt mixtures.

In the context of Türkiye, experimental research on sustainable binder modification has expanded considerably in recent years. Domestic studies report that alternative mineral fillers and waste-based additives exert significant effects on stiffness, aging resistance, and thermal sensitivity of binders. These findings suggest that sustainable binder modification need not be confined to imported polymer additives, but may also be achieved using locally available and industrially derived materials.

From a green logistics perspective, the improvement of binders through sustainable additives is closely associated with extending pavement service life and reducing maintenance frequency. More durable pavements diminish traffic disruptions along logistics corridors and support operational continuity. In addition, reduced reliance on virgin binder production contributes to lower energy consumption and greenhouse gas emissions. Hence, binder modification emerges as an infrastructure-based sustainability tool directly aligned with green logistics goals.

In conclusion, sustainable modification of bituminous binders offers an integrated approach in which environmental performance and mechanical durability are jointly addressed. The use of waste-derived and alternative additives enhances binder performance while reducing natural resource consumption and supporting circular economy strategies. The wider adoption of such practices will enable the development of longer-lasting, low-maintenance, and environmentally responsible pavement systems for green logistics infrastructure.

### **3.5. Relationship between Maintenance Processes and Green Logistics: A Sustainable Pavement Perspective**

Maintenance and rehabilitation activities in pavement systems not only ensure serviceability but also exert direct and indirect influences on the environmental performance of transport operations. The frequency, extent, and methods of maintenance affect transport times, fuel consumption, and emission levels. Accordingly, sustainable pavement engineering regards maintenance processes not merely as technical necessities but as strategic instruments supporting green logistics objectives.

On corridors subject to frequent maintenance, construction zones and traffic restrictions lead to reduced travel speeds and detours, thereby increasing fuel consumption and emissions. These effects become particularly pronounced on logistics corridors carrying heavy vehicle traffic. Consequently, the planning and scheduling of maintenance activities represent critical factors in system-wide efficiency. In this context, the use of sustainable materials that reduce maintenance demand constitutes an indirect yet effective strategy for supporting green logistics.

Through the adoption of recycled and alternative materials, sustainable pavement design aims to extend maintenance intervals and enhance service life. Pavement systems with longer durability reduce energy consumption and emissions associated with maintenance operations. Considering that maintenance activities themselves involve material production, equipment use, and construction logistics, lowering maintenance frequency yields both economic and environmental benefits.

From a green logistics perspective, a strong linkage exists between pavement maintenance and operational continuity. Pavements requiring fewer interventions allow for more predictable logistics planning and reduce disruptions in freight movement. This contributes not only to operational efficiency but also to improved control of transport-related emissions. Sustainable material use in pavements thus functions as an infrastructure-based support mechanism for green logistics objectives.

In the context of Türkiye, the dominance of road transport within logistics systems renders maintenance-related impacts particularly significant. Domestic studies indicate that material- and design-based strategies aimed at reducing maintenance demand can preserve pavement performance while improving operational efficiency. These findings highlight that sustainable pavement practices represent technically viable and environmentally meaningful options for national logistics infrastructure projects.

In summary, maintenance processes and green logistics objectives are directly interconnected through pavement performance. Pavement systems designed with durable, low-maintenance, and environmentally responsible materials contribute to the continuity of logistics operations and to the reduction of transport-related environmental impacts. Maintenance management should therefore be regarded as an integral component of sustainable pavement engineering.

#### **4. Conclusions and Recommendations**

This chapter has examined the sustainability of transportation infrastructure within the framework of green logistics, with particular emphasis on pavement materials and construction practices. The analysis demonstrates that the environmental performance of logistics systems is not determined solely by vehicle technologies and operational strategies, but is also strongly influenced by infrastructure design, material selection, and maintenance processes. This finding underscores that sustainable logistics should be interpreted not only as an operational concept but also as an engineering-based infrastructure challenge.

The sustainability of pavement materials plays a decisive role in terms of natural resource consumption, energy use, and greenhouse gas emissions. Applications such as reclaimed asphalt pavement (RAP), recycled aggregates, and alternative additives constitute practical embodiments of circular economy principles in road construction. These practices reduce the demand for virgin raw materials while lowering the environmental burdens associated with pavement construction. However, sustainability must be evaluated not only with respect to material origin but also in relation to performance over the service life. Pavement systems characterized by long service life, low maintenance demand, and limited performance degradation represent key

elements in securing lasting environmental benefits.

The improvement of bituminous binders through sustainable additives provides an important engineering domain in which environmental and mechanical performance can be addressed simultaneously. The use of waste-derived and rejuvenating agents enables higher utilization of reclaimed materials while controlling aging behavior and extending service life. This approach not only enhances material efficiency but also reduces the environmental impacts associated with maintenance and rehabilitation. Binder modification should therefore be viewed not as a minor technical adjustment but as a structural determinant of pavement sustainability.

The utilization of recycled materials in granular base and subbase layers represents one of the most significant opportunities for sustainability due to the large material volumes involved. Properly designed applications using reclaimed concrete and asphalt aggregates can effectively reduce natural aggregate consumption. Nonetheless, successful implementation requires accurate characterization of material properties, sound engineering design, and systematic quality control. Sustainable material use thus constitutes not merely an environmental preference but an engineering problem demanding rigorous technical discipline.

The relationship between maintenance processes and green logistics emerges as a key conceptual link established in this chapter. Frequent maintenance interventions adversely affect logistics continuity and increase transport-related emissions through traffic disruptions and extended travel times. Sustainable pavement approaches that reduce maintenance frequency thereby support both infrastructure performance and environmental objectives. Pavement systems designed for durability and low intervention enhance predictability in logistics planning and contribute to the mitigation of transport-related environmental impacts.

In the Turkish context, the dominance of road transport in freight movement renders pavement sustainability a strategic concern. Findings from domestic studies indicate that recycled and alternative materials can maintain acceptable engineering performance when applied under appropriate design conditions. This suggests that the integration of sustainable pavement practices into national logistics infrastructure projects represents not only an ecologically desirable choice but also a technically feasible one.

Overall, this chapter demonstrates that the green logistics concept inherently encompasses the physical infrastructure enabling transport operations. Pavement material selection, binder modification techniques, and maintenance management collectively form a structural framework shaping the environmental performance of logistics systems. Sustainable pavement engineering should therefore be regarded not as a supportive element but as

a fundamental engineering component of green logistics strategies. Future research should focus on quantifying these relationships through life-cycle assessment and carbon footprint analyses, as well as expanding project-scale implementation examples.

Given that the approaches discussed herein are largely based on conceptual and literature-driven perspectives, further academic research should prioritize field-based performance monitoring of pavement systems incorporating recycled materials and sustainable additives. Long-term observations under varying climatic conditions and traffic loads will enable more accurate quantification of service life, maintenance requirements, and structural behavior. Comparative performance studies will also strengthen engineering decision-making related to sustainable material use.

Future studies should further integrate life-cycle assessment and carbon footprint analysis to evaluate the influence of sustainable pavement materials on green logistics performance in a comprehensive manner. Such analyses should encompass not only material production stages but also maintenance operations and in-service environmental impacts. In this way, models developed for sustainable pavement design will be capable of explaining logistics-related environmental performance using quantitative indicators.

Moreover, expanding experimental research based on locally available materials and industrial by-products will support the development of design criteria tailored to national conditions. Laboratory investigations and pilot projects focusing on the use of domestic waste streams in asphalt mixtures will contribute to reducing dependence on imported additives while promoting regionally based circular economy solutions.

Finally, the interaction between sustainable pavement systems and green logistics should be examined not only from an engineering performance perspective but also in relation to transport policy and infrastructure management frameworks. Interdisciplinary research models will facilitate a clearer understanding of how pavement material choices influence broader sustainability objectives in logistics systems. Positioning sustainable pavement engineering as an infrastructure-based component of green logistics strategies will thus offer original contributions to both the pavement and logistics literature.

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