

Comparative Analysis of Carbon Footprint in Supply Chain and Logistics Models (JIT, Lean, and Hub & Spoke) for Manufacturing Sector

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Abstract

The global manufacturing sector is currently in dual transition characterized by the pursuit of extreme operational efficiency and the urgent necessity of environmental decarbonization. This research report presents a comparative analysis of three dominant logistics and supply chain architectures - Just-In-Time (JIT), Lean Manufacturing, and Hub & Spoke; evaluating their respective impacts on greenhouse gas (GHG) emissions and overall carbon footprints. Drawing upon extensive secondary data, including urban logistics simulations, automotive sector performance benchmarks and regulatory standards, the analysis explores the "Logistics Carbon Paradox" inherent in high-velocity models, which prioritises on speed, agility, efficiency and real time data to rapidly meet the demands and reducing the inventory holding times. While JIT and Lean principles effectively eliminate "internal" factory waste and minimize warehouse-related energy consumption, they frequently generate "external" transport externalities and scope 3 emissions due to increased trip frequency and fragmented load factors. Conversely, the Hub & Spoke model demonstrates superior performance in load consolidation and total driven distance reduction, as evidenced by simulation data showing up to a 45% reduction in distance and a 32% reduction in CO² emissions when centrally managed. The report further investigates the integration of emerging technologies, such as Artificial Intelligence (AI), Internet of Things (IoT) and digital twins by using systems like SAP, in mitigating these trade-offs. Key findings suggest that the most sustainable outcomes are achieved through a "Leagile-Green" hybrid approach that aligns Lean's waste reduction and agile goals with the structural consolidation advantages of Hub & Spoke networks. The analysis concludes with strategic recommendations for policymakers and industry leaders to harmonize operational excellence with global climate targets, emphasizing the critical role of standardized Scope 3 reporting and the adoption of multimodal transport corridors.

Keywords: Carbon Footprint, Sustainable Logistics, Just-In-Time (JIT), Lean Manufacturing, Hub & Spoke Model, Scope 3 Emissions, Manufacturing Decarbonization, Supply Chain Management.

1. Introduction

The contemporary industrial landscape is undergoing a fundamental transformation where the traditional triangle of supply chain management - cost, speed, and quality; is being expanded to include a fourth non-negotiable dimension: environmental sustainability. Manufacturing, as a cornerstone of the global economy, is a significant driver of resource consumption and greenhouse gas (GHG) emissions. In 2021, the manufacturing sector was responsible for approximately 12% of total U.S. greenhouse gas emissions, with nearly 75% of these emissions resulting from the combustion of fossil fuels for process heat (Congressional Budget Office, 2024a, 2024b). When viewed through a broader industrial lens, these figures can escalate to 23%, positioning manufacturing as the third-largest contributor to direct emissions globally (U.S. Environmental Protection Agency [EPA], 2022).

The imperative cause for decarbonization is no longer a matter of corporate philanthropy but a response to stringent regulatory norms and shifting market demands. The introduction of the European Union's Corporate Sustainability Reporting Directive (CSRD) and the Carbon Border Adjustment Mechanism (CBAM) has forced a radical transparency in how carbon is accounted for across the entire value chain (Greenly, 2026a; Das, 2023). Furthermore, Scope 3 emissions - those occurring in a company's upstream and downstream value chain, often constitute the largest portion of a manufacturer's carbon footprint, typically representing 65% to 95% of total emissions, which depends on the industry, geography, market and many other factors (CarbonChain, 2025; Neo.eco, 2025). With this context, the logistics and supply chain models employed by manufacturers serve as the primary conduits through which carbon intensity is either mitigated or exacerbated.

The three logistics models examined in this report represent distinct operational philosophies. Lean Manufacturing - a comprehensive methodology aimed at eliminating "muda" (waste), provides a holistic framework for efficiency (One Advanced, 2025a). Just-In-Time (JIT) - a critical subset of Lean, focuses on the precise synchronization of inventory with production demands (RFgen, 2025a; EPA, 2024). In contrast, the Hub & Spoke model is a distribution strategy that centralizes inventory to optimize delivery routes and consolidation (Sheer Logistics, 2025; ShipBob, 2025). While each model offers unique competitive advantages, their environmental impacts often diverge, creating complex trade-offs that manufacturers must navigate to achieve net zero targets.

1.1 Research Problem

The core challenge in modern sustainable manufacturing is the inherent conflict between operational agility and carbon footprint reduction as a part of sustainability. High velocity models like JIT are designed to reduce inventory buffers and warehousing costs, which naturally decreases the energy required for climate control for cold chains and costs for maintenance of large facilities like employee salaries, electricity and other miscellaneous costs (EPA, 2024). However, this reduction in "internal" waste often comes at the expense of "external" transport efficiency which connects the different parts of supply chain. The reliance on frequent, small batch deliveries (often referred to as "milk runs") can lead to an increase in total vehicle distance travelled and a significant decrease in vehicle load factors (EPA, 2024; Melo et al., 2022).

This creates the "Logistics Carbon Paradox": a supply chain that is operationally lean and inventory efficient may inadvertently be emissions heavy due to fragmented transportation flows (Melo et al., 2022;

Atlas Copco, 2011). Furthermore, while the Hub & Spoke model offers massive consolidation benefits that reduce driven distances, the extra handling and "circuitry" (the additional distance travelled to reach the hub) can introduce delays that are incompatible with the speed requirements of JIT based urban factories (University of Hannover, 2021; MDPI, 2021). JIT currently suits the fast-moving world with one day delivery and quick commerce being the norms for consumer industry and Lean and agile for industries; whereas, for logistics Hub & Spoke model increase the efficiency and profitability of the transportation industry, which is essential in today's competitive environment. While focusing on both these aspects, one must also analyse and more so implement the sustainability solutions into the industry that create an impact. As supply chain is the interaction of different type of industries, it ought to be that the sustainability practices shall also differ for each stage of the chain. There is currently a lack of empirical consensus on how these models should be integrated to optimize both financial and environmental performance, particularly in mature industrial sectors like automotive and electronics where precision is paramount; for quick commerce and logistics sector where timely delivery and customer satisfaction is of utmost importance.

1.2 Problem Statement

Despite the proliferation of green logistics initiatives, most manufacturers lack the granular comparative data necessary to evaluate the carbon footprint of their supply chain architectures. Traditional accounting methods often fail to capture the secondary and tertiary effects of logistics shifts i.e. the second and third scope emissions. For instance, a transition to JIT might reduce local storage costs but escalate the reliance on high emission air freight to maintain lead times (Das, 2023; Atlas Copco, 2011). Conversely, a Hub & Spoke system might optimize long-haul transport but increase the carbon intensity of the "last-mile" delivery in congested urban environments (Sheer Logistics, 2025; University of Hannover, 2021; MIT, 2024).

The problem is compounded by inconsistent reporting standards. While the GHG Protocol and ISO 14064 provide overarching frameworks, their application to specific logistics models remains varied and often incomplete (Neo.eco, 2025; TZC.ie, 2026a). Consequently, manufacturers face "greenwashing" risks and regulatory non-compliance as they struggle to quantify the true environmental impact of their supply chain decisions (Das, 2023; Salibi et al., 2022). Therefore, there's an urgent need for a systematic, data driven comparison of JIT, Lean and Hub & Spoke models to identify the optimal lean and agile "Leagile-Green" configurations that can support the manufacturing sector's transition to a sustainable economy, while still delivering on the current performance.

2. LITERATURE REVIEW

The study of carbon footprints in manufacturing logistics necessitates an interdisciplinary approach, combining operations management, environmental science and regulatory law. This literature review synthesizes current research regarding the environmental implications of the JIT, Lean and Hub & Spoke models.

2.1 The Environmental Evolution of Lean Manufacturing

Lean Manufacturing, originating from the Toyota Production System (TPS), was initially conceived to enhance productivity by eliminating seven specific types of waste: overproduction, waiting,

transportation, inappropriate processing, excessive inventory, unnecessary motion, and defects (RFgen, 2025a; Autodesk, 2024). While sustainability was not an original tenet of Lean, researchers have identified a natural synergy between Lean and "Green" paradigms. Both focus on resource productivity and the elimination of non-value-added activities (One Advanced, 2025a, 2025b; JIEM, 2022). Focusing on these ensures that the resource is being used optimally via maximum extraction or output from it.

Current academics and research characterize environmental waste as the "eighth waste," encompassing the excessive use of energy, water, and materials (RFgen, 2025b; Green et al., 2019; Leong et al., 2023). Studies have shown that Lean practices like Kaizen (continuous improvement) and Value Stream Mapping (VSM) are highly effective at identifying energy inefficiencies on the production floor (One Advanced, 2025a, 2025b). For example, at Hewlett Packard, the implementation of Lean principles resulted in a 75% reduction in inventory and a 50% reduction in labour costs, which indirectly correlates with a reduced carbon burden through decreased spatial and resource requirements (RFgen, 2025a).

However, the "Lean-Green" relationship is not without contradictions. Some researchers argue that Lean focuses primarily on operational gains, such as lead time reduction, which may lead to efficiency problems if increased energy consumption is required to maintain higher production speeds (Autodesk, 2024; JIEM, 2022). Furthermore, the lack of explicit environmental metrics in traditional Lean tools means that carbon intensive processes may be preserved if they contribute to operational speed (JIEM, 2022; Green et al., 2019).

2.2 Just-In-Time (JIT) and the Transport Emission Paradox

The Just-In-Time (JIT) philosophy represents a subset of Lean focused specifically on inventory management. By producing only what is needed, when it is needed, JIT aims to achieve "zero inventory" (EPA, 2024; Melo et al., 2022). From an environmental perspective, JIT offers several benefits: it reduces the need for large, climate-controlled warehouses, minimizes the risk of product obsolescence or damage during storage, reduces overproduction and decreases the square footage required for production (EPA, 2024; Lean Supply Solutions, 2026).

Nevertheless, the "Logistics Paradox" of JIT is a recurring theme in the literature. Because JIT requires frequent, small volume deliveries to synchronize with production cycles, it often leads to an underutilization of vehicle capacity. This results in more transport journeys, which in turn results in increased fuel consumption, higher maintenance costs due to numerous trips and higher cumulative GHG emissions per unit of product (EPA, 2024; Melo et al., 2022; Gestão & Produção, 2022). Simulations in the consumer goods sector have indicated that JIT arrivals can actually increase transportation related emissions significantly unless offset by superior load planning and route optimization (EPA, 2024; Scribd, 2025b).

Interestingly, JIT can have positive environmental impacts in certain contexts. In the maritime industry, "JIT Arrival" protocols where ships adjust their speed to match port availability can reduce fuel consumption and CO² emissions by approximately 17.6% by eliminating the need for vessels to wait at anchor with their engines idling (Melo et al., 2022). This suggests that the carbon footprint of JIT is highly dependent on the "mode" of transport and the level of systemic synchronization.

2.3 The Hub and Spoke Model: Consolidation and Scale Economies

The Hub & Spoke (H&S) model is primarily a distribution architecture where goods are shipped from various origins to a central "hub" for sorting and consolidation before being distributed to their final destinations or "spokes" (Sheer Logistics, 2025; ShipBob, 2025). This model is the antithesis of Point-to-Point (P-P) distribution and is widely used in the parcel industry and by major logistics providers like FedEx and Maersk (ShipBob, 2025). This model is followed for international trades by virtue of infrastructure and regulatory norms.

The primary environmental advantage of the H&S model is its ability to maximize load factors. By consolidating Less than TruckLoad (LTL) shipments into Full TruckLoad (FTL) or multimodal units (rail/sea/land), the H&S model reduces the number of individual vehicle trips required (Sheer Logistics, 2025; DHL Freight Connections, 2026). Simulation studies for urban factories in Hamburg have shown that a centrally managed Hub & Spoke system can reduce the number of inner city delivery vehicles by nearly 38% and total driven distance by up to 45% (University of Hannover, 2021). This led to a fuel consumption reduction of 31.8% and CO² emission cuts of up to 32% (University of Hannover, 2021).

However, the H&S model can be environmentally detrimental if the hub location leads to excessive circuitry. In the aviation sector, for instance, H&S networks can lead to higher emissions per passenger-mile for passenger aviation or grams of equivalent per tonne-kilometre for air cargo or freight because of the increased number of fuel intensive take-offs and landings associated with connecting flights (MDPI, 2021; IDEAS/RePEc, 2021). For manufacturing, the choice between H&S and P-P involves a trade-off between the carbon savings of consolidation and the carbon costs of additional transit distance and potential hub-induced delays (Atlas Copco, 2011).

2.4 Comparative Performance Metrics in Manufacturing

The literature identifies several key metrics for evaluating the environmental performance of these models. Carbon emission intensity measured as kg CO₂e per ton-km or per unit of production, is the most commonly used metric or unit across all industries (UK DEFRA, 2020; EPA, 2025a; Environmental Economics, 2024). Warehousing metrics, such as kg CO₂e per m² per year, are also critical for comparing Lean and JIT models that impact facility footprints (Fraunhofer IML, 2022; TRA Conference, 2024).

Recent studies emphasize the importance of the "Modal Split" in these models. Because air freight is significantly more carbon intensive than sea or rail, a JIT model that relies on air transport to maintain low inventory levels will have a massive carbon footprint compared to a Hub & Spoke model that utilizes rail for bulk replenishment (Das, 2023; Atlas Copco, 2011; Environmental Economics, 2024). For example, producing one tonne of aluminium produces 10 tonnes of CO₂e, while shipping it around the world contributes less than 1 tonne, unless air freight is used which can double the product's total footprint (Das, 2023; CarbonChain, 2025).

2.5 Scope 3 Accounting and Regulatory Standards

The quantification of carbon footprints in manufacturing is governed by two major frameworks: the GHG Protocol and ISO 14064 (Neo.eco, 2025; TZC.ie, 2026a). The GHG Protocol is highly granular, dividing Scope 3 emissions into 15 distinct categories, such as Category 1 (Purchased Goods and Services) and Category 4 (Upstream Transportation and Distribution) (TZC.ie, 2026a; PMC, 2021a; GHG Protocol,

2024).

ISO 14064 focuses more on the verification and auditability of GHG data, making it the preferred standard for companies seeking third party certification or participating in carbon markets (Greenly, 2026a; TZC.ie, 2026a). As of 2026, new regulations like the EU Green Claims Directive will make it unlawful to use terms like "carbon neutral" without third-party verified proof under standards like ISO 14064 (Greenly, 2026a). This regulatory shift is driving manufacturers to move from "spend-based" emission estimates to more accurate "activity-based" data collection throughout their supply chains (Das, 2023; Solartech, 2025).

These two above standards provide the guidelines for the industry on which companies can measure and calculate their emissions. This allows companies a means to compare their emissions to others companies and the industry average. Companies can also use it to compare with other industrial sectors. These standards also lets researchers compare different industrial sectors and find out which industrial sectors need to be targeted to curtails majority of emissions.

2.6 Industry 4.0 and Digital Decarbonization

The role of digital technology in optimizing logistics models for carbon and emissions reduction is an emerging theme. Artificial Intelligence (AI) and Machine Learning (ML) are being used for real time route optimization, predictive maintenance and smart load building (Das, 2023; DHL Freight Connections, 2026; Marjan & Faisal, 2025). Research indicates that AI-enabled interventions can achieve annual avoided emissions of 500 to 1,500 tCO₂ and reduce fuel consumption by up to 15% (MDPI, 2025a).

Digital twins and IoT sensors allow manufacturers to simulate their logistics networks and identify "carbon hotspots" before making physical changes. These tools can also be used to try out the solutions in simulated environment prior to making actual changes on ground. Learnings from this can then later be used to provide a better solution (Footprints in the Soil, 2024; Megaminds Technologies, 2025). Blockchain technology is also being explored to ensure the traceability of "green" raw materials, such as near-zero steel and recycled aluminium, which are critical for the automotive sector's decarbonization targets (Das, 2023; Footprints in the Soil, 2024). These technologies are transforming JIT and H&S from static models into dynamic, responsive systems capable of prioritizing both efficiency and environmental impact.

3. RESEARCH METHODOLOGY

The methodology for this research report follows a structured approach to synthesize and interpret technical data related to supply chain carbon footprints.

3.1 Objectives

The primary objectives of this comparative analysis are:

1. To evaluate the environmental impact of JIT, Lean and Hub & Spoke models on the manufacturing sector's carbon footprint.
2. To quantify the trade-offs between inventory reduction (JIT/Lean) and transport consolidation (Hub & Spoke).

3. To analyse the role of regulatory frameworks (GHG Protocol, ISO 14064) and digital technologies in standardizing and reducing emissions.
4. To provide evidence based recommendations for manufacturers to optimize their logistics models for sustainability.

3.2 Nature and Sources of Data

This report utilizes secondary data derived from a variety of authoritative sources, including:

- Peer-reviewed academic journals (Autodesk, 2024; JIEM, 2022; MDPI, 2024).
- Technical reports and circulars from international bodies (MDPI, 2021; Planbe.eco, 2026; OECD, 2021).
- Regulatory standards and guidance documents (TZC.ie, 2026a; PMC, 2021a; EPA, 2025a).
- Simulation-based feasibility studies (Melo et al., 2022; University of Hannover, 2021).
- Industry-specific leaderboard reports and trend studies (Footprints in the Soil, 2024; Lead the Charge, 2025a, 2025b).

3.3 Inclusion and Exclusion Criteria

The data selection followed a systematic methodology:

- **Inclusion:** Sources published between 2011 and 2025; research specifically addressing JIT, Lean or Hub & Spoke models in a manufacturing or distribution and logistics context; quantitative data on GHG emissions or carbon intensity; peer-reviewed or institutionally authoritative reports.
- **Exclusion:** Sources focused solely on passenger transport or retail only logistics; non-English publications without accessible translations; and speculative or non-empirical whitepapers without underlying data support.

3.4 Analytical Approach

The analysis employs a **Thematic Synthesis** methodology. Findings from diverse sources were coded and categorized into themes: operational efficiency, transport intensity, facility carbon footprint and regulatory compliance (Scribd, 2025a). This approach allows for the integration of heterogeneous data, such as urban simulation results and macro level industry trends into a cohesive narrative that identifies cross model synergies and contradictions among them (Scribd, 2025a; PMC, 2021b).

3.5 Hypothesis

Based on the preliminary literature review, the following hypotheses are tested through data interpretation:

- **H₁ (Consolidation Effect):** The Hub & Spoke model significantly reduces transport related carbon emissions compared to decentralized Point-to-Point models through improved load factors and route optimization.
- **H₂ (JIT Paradox):** JIT logistics models increase a company's transport carbon footprint per ton-km compared to Lean models with larger inventory buffers, due to increased delivery frequency.
- **H₃ (Technology Mediation):** The integration of AI and real time visibility tools mitigates the negative environmental impacts of JIT by optimizing trip frequency and ensuring higher vehicle occupancy.

3.6 Limitations of the Study

This research is constrained by several factors:

- **Secondary Data Dependence:** The analysis relies on previously published research; therefore, the quality and boundaries of the original data vary.
- **Rapidly Evolving Landscape:** Technological shifts in electrification and renewable fuels are occurring at a pace that may outdate specific 2024-2025 statistics by the time of implementation (Footprints in the Soil, 2024; Automotive Logistics, 2025).
- **Geographic Bias:** Much of the available literature focuses on North American, European, and Chinese manufacturing contexts, with less data available for emerging markets in the Global South (Melo et al., 2022).
- **Scope 3 Data Maturity:** Since Scope 3 accounting is still maturing, many industry reported figures may still rely on spend based estimates rather than primary activity data (GHG Protocol, 2024; Solartech, 2025). Also, scope 3 data sourcing is from companies' own websites and report documents rather than a 3rd party or institutional reports.

4. DATA INTERPRETATION AND ANALYSIS

This section presents a detailed interpretation of the collected data, testing the research hypotheses and exploring the nuances of each logistics model.

4.1 Carbon Intensity and Transport Efficiency

The environmental impact of logistics is largely dictated by the "Ton-Kilometer" (ton-km) metric, which measures the transportation of one ton of cargo over one kilometer. The emission factor (EF) for this metric varies drastically by mode.

4.1.1 Comparing Emission Factors by Mode

As demonstrated in the table below, the choice of transport mode is the single most important factor in a logistics model's carbon footprint.

Transport Mode	Emission Factor (kg CO ₂ e / ton-km)	Comparative Impact	Sources
Air Freight	0.50 – 1.50	Highest: Used for high-speed JIT	Das, 2023; Atlas Copco, 2011
Road (Heavy Truck)	0.07 – 0.12	Moderate: Standard for JIT/Lean	UK DEFRA, 2020; EPA, 2025a; Environmental Economics, 2024

Rail (Freight)	0.002 – 0.015	Low: Ideal for H&S hub-to-hub	EPA, 2025a; Environmental Economics, 2024
Maritime (Cargo Ship)	0.001 – 0.015	Lowest: For global Lean supply chains	Melo et al., 2022; UK DEFRA, 2020

Table 1: Environmental Performance of Transport Modes in Supply Chain Operations

Analysis of H₁ (Consolidation Effect): The data supports H₁. By utilizing a Hub & Spoke architecture, manufacturers can shift long haul flows from road to rail or sea, leveraging the lower emission factors of these modes. For the geographies like Europe and America, train travel can be a great alternative for controlling emissions. Air travel is the highest emitter and an expensive option monetarily also, and so must be used only at times when no other option is viable. Air travel can altogether be avoided if advance planning is done for a supply chain. Furthermore, the Hub & Spoke model facilitates the consolidation of LTL into FTL, which reduces emissions by 14% to 32% compared to base-scenario point-to-point deliveries (University of Hannover, 2021).

4.1.2 The JIT Logistics Paradox: Frequency vs. Volume

JIT’s focus on small, frequent deliveries inherently conflicts with the goal of maximizing load factors. A study on JIT arrivals in maritime transport showed that while speed optimization can save 17.6% of CO₂, the terrestrial application of JIT often has the opposite effect (Melo et al., 2022). This means that JIT for road transportation leads to more carbon emissions and also a lower logistical efficiency than H&S model.

Model Component	Environmental Benefit	Environmental Cost	Sources
Inventory Buffer	Reduced obsolescence and spoilage	Higher transport frequency	Melo et al., 2022; EPA, 2024
Warehouse Space	30%–50% reduction in square footage	Lower vehicle occupancy rates	Lean Supply Solutions, 2026; Melo et al., 2022
Precision Timing	Reduced idle times at loading bays	Reliance on faster, dirtier modes (Air)	Melo et al., 2022; Atlas Copco, 2011

Table 2: Environmental Trade-offs of Key Lean Logistics Model Components

Analysis of H₂ (JIT Paradox): The evidence confirms H₂. While JIT makes the factory "lean" internally, it tends to make the logistics network "heavy" externally. Unless JIT is implemented with extreme load planning (e.g., "Milk Runs" where one truck visits multiple suppliers), the transport footprint per unit remains higher than in models with larger batch sizes (EPA, 2024; Melo et al., 2022).

4.2 Urban Logistics and Manufacturing Sites

The integration of manufacturing into urban areas (urban factories) highlights the effectiveness of the Hub & Spoke model for the "last mile."

4.2.1 Hamburg Simulation Results: Hub vs. No-Hub

Metric	Base Scenario (No Hub)	Scenario 3 (Best Hub)	Variance (%)
Total Vehicles	900	560	-37.78%
Total Driven Distance (km)	7,476.63	4,105.27	-45.09%
Fuel Consumption (L)	1,729.87	1,179.08	-31.84%
Vehicle Occupancy	66.16% - 78.52%	91.39% - 97.66%	+38% (Avg)

Table 3: The simulation based on the city of Hamburg evaluated industry-related deliveries under different scenarios. Source - University of Hannover, 2021

A critical finding from this study was that **all JIT deliveries** were successfully met within their time windows while using the hub (University of Hannover, 2021). This refutes the idea that Hub & Spoke models are inherently incompatible with JIT precision. By decoupling the "macro-flow" (to the city boundaries) from the "micro-flow" (within the city), the hub acts as a buffer that actually improves delivery reliability in congested areas (University of Hannover, 2021).

4.2.2 Warehouse and Hub Emission Intensity

While transport dominates the carbon footprint, the operational emissions of logistics sites are not negligible.

Logistics Site Type	Avg Emission Intensity (kg CO _{2e} / tonne)	Avg Emission Intensity (kg CO _{2e} / m ²)
Transshipment Hub	0.5 - 3.6	10.2 - 55.3
Storage + Transshipment	2.1 - 11.1	58.8 - 61.9
Standard Warehouse	27.8	12.6 - 14.9

Table 4: Emission intensity based on logistical sites. Source - Fraunhofer IML, 2022

Interpretation: JIT's strategy of minimizing storage reduces the reliance on high intensity "Storage + Transshipment" sites, shifting the burden toward "Transshipment Hubs" which have lower emissions per tonne of throughput (Fraunhofer IML, 2022). This facility-level shift partially offsets JIT's transportation burden as this solution provides a direct route for goods to move from supplier to consumer without any intermediary.

4.3 Industry Specific Case Studies

The carbon footprint of these models is significantly influenced by industry characteristics. The sectoral trends in 2024 - 2025 have shown a changing pattern. The industry, particularly for consumer products is shifting to quick commerce wherein the delivery is within a day at max and within few hours for majority of the orders. While the e-commerce is still relevant and a huge section for consumer goods, it still strives to deliver the goods within a day to make up with the quick commerce and within a week at maximum. It is only time when the commercial industry will also move to these delivery timings. This will require therefore a resilient supply chain if these requirements and standards are to be sustained.

4.3.1 The Automotive Sector: Balancing JIT and Resilience

The automotive industry is the pioneer of JIT and Just-In-Sequence (JIS) deliveries (University of Hannover, 2021; Uber Freight, 2024). However, 2025 reports indicate that the industry is making "slow and inadequate progress" on cleaning up its supply chains, with no major automaker achieving a score over 50% on sustainable supply chain leaderboards (Lead the Charge, 2025b).

Automotive logistics are shifting toward "nearshoring" or "trade insulated" sourcing in response to trade volatility and improving supply chain resilience (Automotive Logistics, 2025; S&P Global, 2025). This localization of the supply chain is a powerful decarbonization lever, as it reduces the absolute distance travelled by heavy components like engines and batteries (Footprints in the Soil, 2024; S&P Global, 2025). Furthermore, by 2025, recycled materials comprise 50% of interior components and some plants (e.g., BMW's) are running 100% on renewable energy, significantly lowering Scope 1 and 2 emissions (Footprints in the Soil, 2024).

4.3.2 Electronics and Prefabricated Construction

In high value, fast moving industries like electronics, JIT is essential. 70-90% of electronics emissions come from component manufacturing, meaning logistics must be optimized to ensure these high-impact items are used efficiently without obsolescence (Das, 2023).

In the prefabricated building sector, the logistics stage has a higher carbon footprint than traditional construction because components are large, heavy and require multiple specialized vehicle trips (MDPI, 2023). A study showed that increasing the full-load rate can reduce these transportation emissions by 54.32%, reinforcing the value of the Hub & Spoke consolidation principle even in non-traditional manufacturing sectors (MDPI, 2023).

4.3.3 Pharmaceutical Logistics and Cold Chain

The pharmaceutical industry, particularly for biologics, has extreme variation in carbon footprints. First-year treatment emissions for monoclonal antibody therapies can range from 1.1 kg CO_{2e} to 188.9 kg CO_{2e}, a 172 fold difference driven by dosing practices and manufacturer energy sources (PubMed, 2025). For

these products, JIT is not just an efficiency choice but a safety requirement as some drugs might have a time limit as they degrade over time. Due to this in some cases cold chain needs to be used in order to extend the life time of the drug in order to complete the journey. Therefore, decarbonization path for pharmaceutical logistics involves optimizing dosing and utilizing renewable electricity in "Sustainable Logistics Hubs" (TRA Conference, 2024; PubMed, 2025).

4.4 Regulatory Compliance and Standardized Accounting

The transition to low-carbon logistics is increasingly driven by mandatory reporting. The "GHG Protocol vs. ISO 14064" debate is central to manufacturing strategy.

Feature	GHG Protocol	ISO 14064	Sources
Primary Focus	Detailed accounting logic (15 Categories).	Verification and auditability.	ISO 14064-3, TZC.ie, 2026a
Scope 3 Application	Granular guidance for supply chain hotspots.	Formal certification for investors.	Greenly, 2026a; TZC.ie, 2026a
Adoption	Required for CDP and SBTi disclosures.	Ideal for contractual bidding and ESG audits.	TZC.ie, 2026a, 2026b

Interpretation: Manufacturers are increasingly adopting a "Hybrid Use" approach, using the GHG Protocol for the internal calculation of JIT/H&S trade-offs while using ISO 14064 to verify these figures for external stakeholders (Neo.eco, 2025; TZC.ie, 2026a, 2026b). This dual approach is essential to survive the "end of vague green claims" predicted by 2026 (Greenly, 2026a).

4.5 The Impact of Digitalization and AI (Testing H₃)

Digital tools are the primary mediators of logistics carbon footprints in the 2024-2025 landscape.

- **Route Optimization:** AI interventions achieve a 12-15% reduction in fuel consumption by identifying the most efficient routes and avoiding empty runs (MDPI, 2025a, 2025b).
- **Predictive Maintenance:** IoT and sensors proactively predict component failures, cutting downtime by 30% and reducing the need for high-emission "emergency" air freight deliveries (Footprints in the Soil, 2024).
- **Asset Tracking:** Real time visibility solves the "ghost inventory" problem, allowing JIT systems to operate with smaller safety stocks without increasing risk (Lean Supply Solutions, 2026).
- **Decarbonization Planning:** Multi-period combinatorial optimization models guide fleet transition from diesel to electric, helping companies leverage network wide cost benefits (MIT, 2024).

Analysis of H₃ (Technology Mediation): The data supports H₃. Technology acts as a "decoupling" agent that allows JIT systems to maintain responsiveness while achieving the load factors and route efficiencies

traditionally associated with Hub & Spoke models. This is particularly evident in the "Milk Run" systems used in the automotive sector, which are entirely dependent on digital scheduling and visibility (Melo et al., 2022; Uber Freight, 2024).

5. FINDINGS, CONCLUSION AND RECOMMENDATIONS

This section synthesizes the analysis into actionable findings and a comprehensive conclusion on the carbon footprint of manufacturing logistics models.

5.1 Major Findings

The comprehensive analysis of secondary data and simulations identifies the following major findings:

1. **The Superiority of Centrally Managed Consolidation:** The Hub & Spoke model is the most effective architecture for reducing the absolute carbon footprint of logistics. By increasing vehicle occupancy to over 90% and reducing driven distance by up to 45%, it achieves a CO₂ reduction of 14% to 32% compared to decentralized models (University of Hannover, 2021).
2. **The JIT Environmental Paradox:** While JIT effectively eliminates internal factory waste and minimizes warehouse energy use, it creates a "logistics paradox" where increased delivery frequency significantly raises transport emissions unless meticulous load consolidation (e.g., Milk Runs) is employed (EPA, 2024; Melo et al., 2022).
3. **Lean Green Synergy:** Lean principles provide a critical cultural and operational baseline for sustainability. Process improvements like Kaizen and VSM are essential for identifying energy waste, and Lean manufacturers naturally adopt Green practices more effectively than non-Lean organizations (One Advanced, 2025a, 2025b; JIEM, 2022).
4. **The "Modal Split" as the Primary Driver:** The choice between Air, Road, and Rail/Sea is more significant than the choice between JIT, Lean and H&S. A JIT system using air freight will always have a carbon footprint orders of magnitude higher than an H&S system using rail (Das, 2023; Atlas Copco, 2011; Environmental Economics, 2024).
5. **Regulatory Imperative:** Manufacturers are shifting from voluntary reporting to audit-ready compliance under ISO 14064 and GHG Protocol Scope 3 standards. This shift is exposing the "hidden" carbon burden of global supply chains, where Scope 3 often represents 80 - 90% of total emissions (Greenly, 2026a; Das, 2023; Neo.eco, 2025; Solartech, 2025).
6. **Digital Transformation as a Decarbonization Lever:** AI and digital twins are enabling a 12 - 15% reduction in fuel consumption and a 30% reduction in downtime, making "Leagile-Green" hybrid models a reality (MDPI, 2025a; Footprints in the Soil, 2024; Megaminds Technologies, 2025).

5.2 Conclusion

The comparative analysis of JIT, Lean, and Hub & Spoke models indicates that no single architecture is a universal environmental panacea. Instead, the most sustainable manufacturing supply chains are those that adopt a "**Leagile-Green**" hybrid approach.

In this hybrid framework, **Lean** principles are used to eliminate internal process waste and optimize the carbon efficiency of the production floor. **Hub & Spoke** architectures are utilized for the macro-level logistics (upstream sourcing and regional distribution) to capture the massive carbon benefits of

consolidation and multimodal transport (Rail/Sea). Finally, **JIT** protocols are applied to the "last mile" or the final assembly sequence, where synchronization is critical to avoid the waste of overproduction and inventory obsolescence.

The research refutes the notion that JIT is inherently incompatible with carbon reduction. Rather, it demonstrates that JIT's environmental performance is a function of the **logistics infrastructure** and **digital visibility** that supports it. When JIT is integrated into a Hub & Spoke network for urban factories, it can meet strict time windows while still benefiting from the 32% CO₂ reduction achieved through consolidation (University of Hannover, 2021).

Ultimately, the future of manufacturing logistics lies in "**Localized Resilience.**" The trends of 2024 - 2025 point toward nearshoring and trade-insulated cost structures, which naturally shorten supply chains and reduce the carbon footprint of transportation (Automotive Logistics, 2025; S&P Global, 2025). Combined with the transition to 100% renewable powered factories and AI driven route optimization, the manufacturing sector is finally developing the tools to decouple economic output from environmental damage.

5.3 Recommendations

The following suggestions are derived from the technical analysis and are directed toward manufacturing executives, logistics managers and policymakers:

- **For Manufacturing Executives:**
 - Transition your carbon accounting from "spend based" to "activity based" reporting by 2026 to ensure compliance with the EU Green Claims Directive and CSRD (Greenly, 2026a; Solartech, 2025).
 - Implement "Kaizen with Green Goals" as a standard part of the continuous improvement cycle, empowering workers to identify and eliminate energy and material waste on the shop floor (One Advanced, 2025a, 2025b).
 - Invest in "Digital Twins" of the supply chain to simulate the carbon impact of moving between JIT, Lean and H&S configurations before committing to physical infrastructure changes (Megaminds Technologies, 2025).
- **For Logistics and Supply Chain Managers:**
 - Prioritize "Milk Run" systems and digital load building to mitigate the JIT transport paradox. Ensure that high delivery frequency is always paired with high vehicle occupancy (EPA, 2024; DHL Freight Connections, 2026; Uber Freight, 2024).
 - Utilize Hub & Spoke architectures for regional consolidation, leveraging rail freight for hub-to-hub links to capture a 30x reduction in carbon intensity compared to road transport (Environmental Economics, 2024).
 - Redesign JIT arrivals for maritime and international freight to eliminate port idling times, potentially saving up to 17.6% of voyage emissions (Melo et al., 2022).
- **For Policymakers and Industrial Planners:**
 - Incentivize the development of "Sustainable Logistics Hubs" (ISO 14083) that integrate renewable energy generation and multimodal transshipment capabilities (TRA Conference, 2024).
 - Encourage the "Nearshoring" of critical manufacturing sectors (automotive, semiconductors)

through trade-insulated cost frameworks to shorten supply chains and reduce absolute carbon footprints (Automotive Logistics, 2025; S&P Global, 2025).

- Mandate a standardized "Carbon Passport" for manufactured components, particularly in the automotive and electronics sectors, to ensure transparency in Scope 3 emissions across global value chains (Das, 2023; Footprints in the Soil, 2024).
- **For Technology and Academic Communities:**
 - Focus on the development of affordable, AI-based route optimization tools that can be deployed by SMEs in the manufacturing sector (Marjan & Faisal, 2025; MDPI, 2025a).
 - Develop unified "Leagile-Green" frameworks that integrate operational KPIs (Lead time, Inventory turns) with environmental KPIs (kg CO₂e per unit) in a single real-time dashboard (Gestão & Produção, 2022; Studocu, 2022).

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