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THE PARADOX OF DIGITAL TRANSFORMATION: HOW INCREASING DATA CENTER ENERGY CONSUMPTION FOR DIGITAL LOGISTICS AFFECTS NET-ZERO GOALS

Gao Xianghong^{1*}, Abu H. Ayob²

¹ Faculty of Economics and Management, Universiti Kebangsaan Malaysia, Malaysia

 p133983@siswa.ukm.edu.my

 <https://orcid.org/0009-0002-3537-3483>

² Faculty of Economics and Management, Universiti Kebangsaan Malaysia, Malaysia

 abuhanifah.ayob@ukm.edu.my

 <https://orcid.org/0000-0001-9759-7381>

*Corresponding Author

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Abstract:

The rapid evolution of digital technologies in supply chains and logistics domains is widely regarded as an enabler of achieving global and corporate net-zero visions. However, this vision overlooks a fundamental paradox: the carbon and energy cost of the digital infrastructure (e.g., artificial intelligence, data centers, and cloud computing) required to make these efficiencies affordable is massive and rising exponentially. This study introduces a new theoretical approach to quantitatively examine this "digital sustainability paradox." We develop a discrete-event simulation model of a multi-echelon supply chain to compare the quantity of carbon reduced by optimizing logistic operations with that of the carbon emissions caused by the enabling digital infrastructure. Our scenario analysis reveals that while digital transformation always increases operational effectiveness, overall carbon impact may not necessarily be minimized. The study's most significant discovery is that the environmental benefits of digital logistics are very much contingent upon the source of energy powering the data centers. We demonstrate that without substituting to renewable power for digital equipment, carbon reductions from efficiency improvements are largely reversed, and in some cases, the total carbon footprint increases. This research provides a critical and integrated perspective on the green implications of digitalization, providing actionable policy recommendations for policymakers and practitioners to ride out this paradox and guide a truly sustainable digital future.

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Carbon Footprint, Data Center Energy, Digital Logistics,
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Introduction

In the pursuit of greater efficiency, resilience and sustainability, logistics, operations and supply chain management are being transformed by digitalization. The Internet of Things (IoT), artificial intelligence (AI), machine learning, and blockchain technologies are employed to automate everything from demand forecasting and route planning to inventory management and warehouse automation (Singh 2025). The promise is clear-cut: an "intelligent" supply chain can eradicate waste, reduce empty miles, and enhance visibility into operations, thus directly supporting corporate and global net-zero carbon emissions ambitions (Ojadi et al. 2023). However, this digital progress story tells a hidden but evident paradox. As much as information technologies are commonly heralded as a panacea for sustainability issues, their physical infrastructure with the most significant ones is such as data centers, cloud computing and advanced computing operations use staggering and increasing amounts of power. The International Energy Agency (IEA) reported that global data centre electricity consumption, which represents approximately 1.5% of global electricity demand in 2024, is projected to grow exponentially due to the widespread adoption of AI and big data analytics across all sectors, including logistics (IEA, 2024). Figure 1 below illustrates the projection till year 2030.

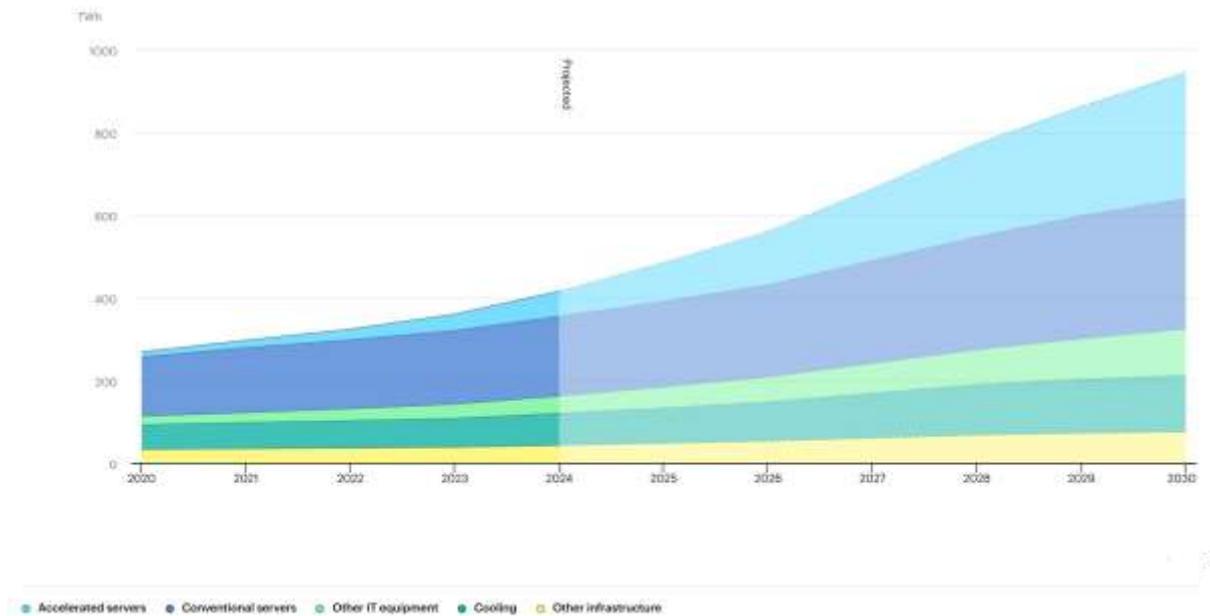


Figure 1: Projection of Global Data Centre Electricity Consumption from Year 2020 till Year 2030 by Equipment

Source: IEA

This raises the important but poorly explored question which is, does energy saving on the "front-end" of a digitalized supply chain actually offset the energy consumed by the "back-end" data infrastructure or are we simply shifting the environmental footprint by masking it? This paper addresses this paradox by examining the end-to-end carbon footprint of digital transformation in the logistics arena. We challenge the conventional assumption that digital technologies are a direct boon to supply chain sustainability. Instead, we propose a methodology for systematically analyzing the trade-offs between the carbon emissions avoided through operation efficiencies and the emissions generated by enabling digital infrastructure. This research is motivated by the need to better understand how technology decisions impact the environment, more than in terms of efficiency to a more holistic lifecycle assessment. This research is adding to the supply chain sustainability and digitalization body of knowledge in three important ways.

First, we develop a new conceptual framework which better explains the paradoxical relationship between digital logistics and net-zero ambitions fully embracing the hidden energy cost of data processing and storage. Second, we provide a qualitative explanation through a simulation model or illustrating the scale of this trade-off, underlining the conditions under which the "paradox" represents an actual barrier to sustainability goals. Finally, we offer actionable policy and management recommendations for solving this paradox, guiding policymakers and companies toward a more genuinely sustainable and ethical digital age.

Overall, this study contributes to the literature by situating digital supply chain transformation within a lifecycle sustainability framework. While most prior research focuses on operational efficiency as a proxy for environmental benefit, we highlight that true sustainability requires a systems-level assessment that considers both the front-end operational gains and the back-end energy footprint of digital infrastructures. By doing so, we provide a conceptual and empirical

basis for understanding the “digital sustainability paradox,” offering a framework that bridges supply chain sustainability, digital transformation, and lifecycle assessment research.

Literature Review and Conceptual Framework

To fully understand the paradox that we are exploring, it is essential to synthesize three distinct streams of literature: (a) the role of digital technologies in supply chain management, (b) research on supply chain sustainability and net-zero goals, and (c) the energy consumption of digital infrastructure.

Digital Transformation for Sustainable Supply Chains

A vast and growing body of literatures have shown that digital transformation is able to enhance operational effectiveness and also sustainability (Stroumpoulis & Kopanaki, 2022). The primary argument is that digital technologies enable greater visibility, real-time data, and predictive analytics that enable companies to make improved choices that reduce waste and resource consumption. This has been the dominant direction of post-pandemic research, and technology like big data, blockchain, AI, and IoT have been the prime drivers of this shift (Paramesha et al., 2024).

One of its primary applications is the use of the IoT is to reduce the carbon footprint of transportation. IoT sensors on assets and vehicles provide a steady stream of real-time data on vehicle location, fuel consumption, and vehicle performance. This data, once optimized by effective algorithms, helps in sophisticated route optimization saving distance, avoiding traffic congestion, and minimizing downtime, which translates into vast fuel savings and smaller carbon footprint (Alsamhi et al. 2019). In this case, Synergy (2025) has reported fuel savings of 10-15% utilizing these methods. Apart from that, AI and machine learning have revolutionized demand forecasting. Traditional forecasting methods will often lead to overproduction and warehousing, which in turn amounts to unnecessary wastage of materials, energy, and transportation resources (Pal, 2023). In this regard, machine learning platforms can process enormous amounts of data from various resources which ranges anything from historical sales and weather patterns to social media sentiment through which, very accurate, detailed forecasts can be generated. This precision allows companies to align output and inventory levels more precisely with actual demand and thereby prevent waste and reduce the need for costly and carbon-intensive last-minute transport (Ojadi et al. 2024).

Blockchain technology has also been advocated as a lead enabler for green supply chains where through the creation of a clear, unalterable, and decentralized ledger, blockchain enhances material and product traceability from source to consumer (Vazquez Melendez et al. 2024). Transparency is needed in order to authenticate the sustainability of products, track carbon footprints across the supply chain, and ensure compliance with environmental and ethical standards. It fosters confidence among stakeholders and functions to prevent fake "greenwashing" claims (Silkose & Nygaard, 2025). In essence, the prevailing perception in this space is that digital technologies are a key enabler for achieving sustainability goals, acting as agents of operating improvements with immediate consequences for the environment. Most research, however, focuses on the efficiency gains alone without examining the overall lifecycle impact of the technologies themselves.

Supply Chain Sustainability and Net-Zero Targets

The search for supply chain sustainability has shifted from the periphery to the center of strategic imperative driven by an intersection of regulatory needs, customer demand, and investor expectations (Hsu et al. 2013). Supply chain sustainability is usually addressed using the triple bottom line where performance is measured in three pillars which are people, planet and profit. Though all three are interconnected, the "planet" pillar, particularly the pursuit of net-zero emissions, has been the prevailing agenda for the majority of companies. A foundation for understanding and measuring corporate carbon footprints is the Greenhouse Gas (GHG) Protocol, which is broken down into three scopes (Accounting 2004). Scope 1 has direct emissions from company-owned or company-controlled sources (company vehicles, combustion of fuels on company premises). Scope 2 includes indirect emissions from electricity, steam, heating, and cooling purchased by the company.

Critically, Scope 3 consists of all the other indirect emissions which occur in the value chain of a firm, upstream (e.g., raw material production, purchase of goods) and downstream (e.g., distribution and transport, end-of-life product management). For the majority of modern supply chains, Scope 3 emissions are the largest and most complex portion of their total carbon footprint, typically accounting for over 70-80% of total emissions (Huang et al. 2009). Figure 2 below shows the illustration of the three Scopes by GHG.

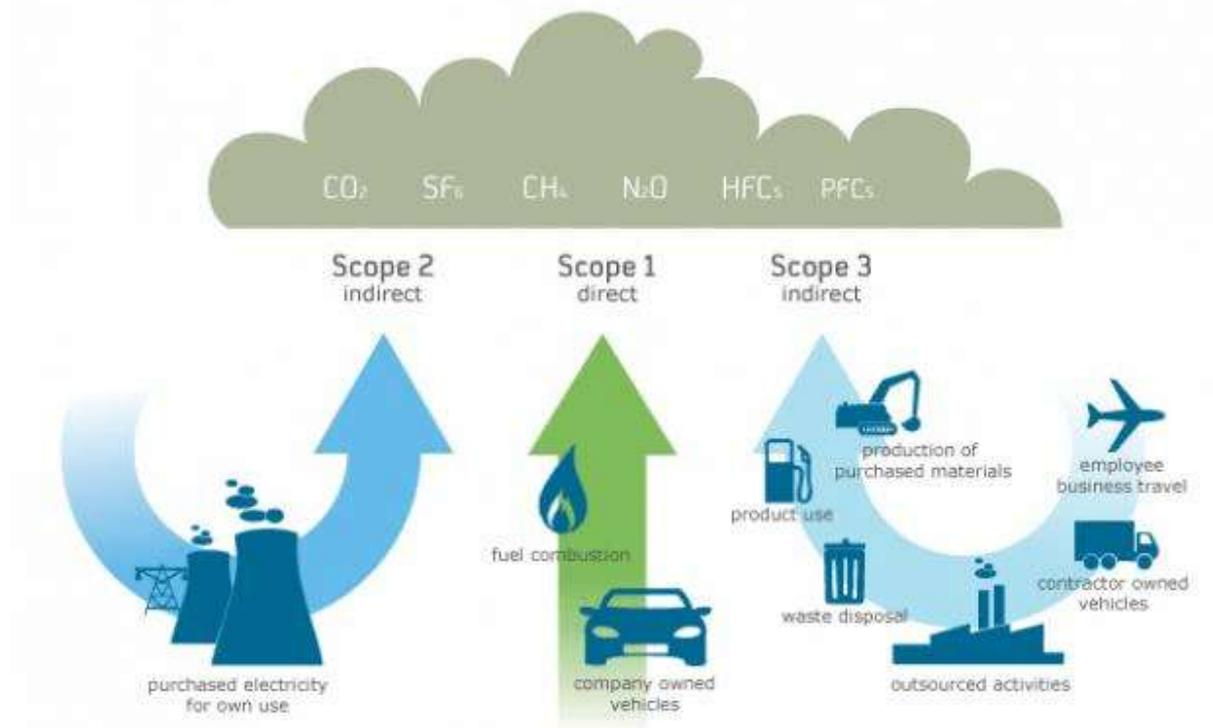


Figure 2: Classification of Scope 1, Scope 2 and Scope 3 Emissions

Source: Greenhouse Gas

The push for companies to embrace and achieve net-zero targets is multidimensional. Governments around the world are establishing more stringent laws, such as the EU Corporate Sustainability Reporting Directive (CSRD), calling for transparent disclosure of environmental footprints (TODESCHINI 2024). Customers simultaneously are more and more backing firms

with better sustainability track records, while investors are using Environmental, Social, and Governance (ESG) metrics as the core component of their valuation and risk framework. Responding to this, an increasing number of firms are signing up to international schemes such as the Science Based Targets initiative (SBTi), which offers a template for emissions reduction targets that are consistent with the aims of the Paris Agreement (Bjørn et al. 2021).

However, the task of going towards net-zero in the supply chain is not easy, more particularly with regards to measuring and managing Scope 3 emissions. Data required to properly calculate these emissions are dispersed, being with a big and diverse group of suppliers, partners, and customers. Companies also seldom have the visibility and direct control to influence the operations of its upstream and downstream partners. In addition to that, the use of industry averages or spend-based estimates that has been long incorporated in the industries can result in inconsistencies that makes it difficult to determine and prioritize reduction strategies (Liu et al. 2025). Summing up, this section establishes that making supply chains sustainable is an advanced and information-intensive task, and that Scope 3 emissions are the largest hurdle.

The Hidden Energy Cost of Digital Infrastructure

Whereas Sections 2.1 and 2.2 show the potential for digital technologies to make supply chains more sustainable, they overlook the considerable and growing energy footprint of the digital infrastructure itself. The same solutions that are supposed to reduce emissions from physical operations incur a significant "back-end" emissions burden from their computation requirement.

This hidden expense is concentrated in two main regions: data centers and energy-hungry processes of next-generation computing, namely those associated with AI (Ahmed et al. 2021). Data centers, where the servers and storages for cloud computing and big data analytics are housed, are some of the most energy-hungry buildings in the world. The energy consumed by this digital system is not a one-time cost, but increases proportionally with the sophistication and volume of data being processed (Goel et al. 2024). The sophisticated algorithms employed by AI-based demand forecasting, for example, consume massive amounts of computational resources, and the training of one large AI model can consume as much power as a few houses per year. In addition to that, the constant processing of IoT sensor for real-time inventory tracking and fleet optimization adds on to a consistent and rising of energy load.

Most importantly, this digital infrastructure's carbon footprint depends mainly on the energy source that it is driven by (Yu & Hu 2024). Thus, when cloud services and data centers are powered with fossil fuels, every gigabyte of data processed, and every algorithm run contributes to the worldwide greenhouse gas emissions that defeats the sustainability goals. In other words, it is basically passing the carbon burden from the Scope 1 and 2 emissions of an organization (such as transportation and facility energy usage) to the Scope 3 emissions of their cloud computing company. This reallocation of emissions complicates corporate net-zero targets and is a significant obstacle for those firms that turn to digital fixes without first exploring their underlying energy mix. This creates the "digital sustainability paradox" at the heart of our work: the very technologies used to meet the carbon challenge in the supply chain could be a new and significant source of emissions in and of themselves.

Methodology

It is only through the literature review that it becomes apparent there is a vast research gap at the intersection of these three domains. Most of the studies on logistic and supply chain management are focused on the operational benefits of digitalization with little examination of the environmental cost of the supporting data infrastructure. Conversely, data center energy consumption studies barely place such consumption into context within a specific business application, such as logistics. Therefore, in this paper we propose to bridge this gap by describing a conceptual framework to investigate the "digital sustainability paradox." We will idealize and approximate the trade-off between the carbon gain of optimized logistics processes and the carbon cost of the computing power required in order to optimize them. In doing so, we aim to give a better and more complete description of the actual environmental impact of digital transformation.

Conceptual Framework and Modelling Approach

To quantify the "digital sustainability paradox" in a systematic and replicable manner, this study employs a discrete-event simulation (DES) model. DES is a widely accepted and powerful technique in operations and supply chain management for modeling complex systems with stochastic (random) elements and a sequence of discrete events. This approach allows us to compare the total carbon footprint of a traditional supply chain against that of a digitally transformed one under varying conditions, thereby providing a clear, quantitative basis for our analysis.

Our core conceptual model is designed to measure the trade-off between two primary emission streams:

1. Logistics Emissions (Elogistics): The direct carbon emissions (kgCO₂e) from the physical movement of goods, primarily from fuel consumption by vehicles.
2. Digital Emissions (Edigital): The indirect carbon emissions (kgCO₂e) generated by the energy consumed by the digital infrastructure (e.g., IoT sensors, AI models for forecasting and routing, cloud data storage) that enables operational efficiencies.

The total carbon footprint of the supply chain (E_{total}) is therefore defined as the sum of these two components:

$$E_{total} = E_{logistics} + E_{digital} \quad (1)$$

The paradox is observed when a reduction in Elogistics from digital optimization is equal to or less than the simultaneous increase in Edigital. With that being said, Figure 3 below shows the conceptual framework for the model.

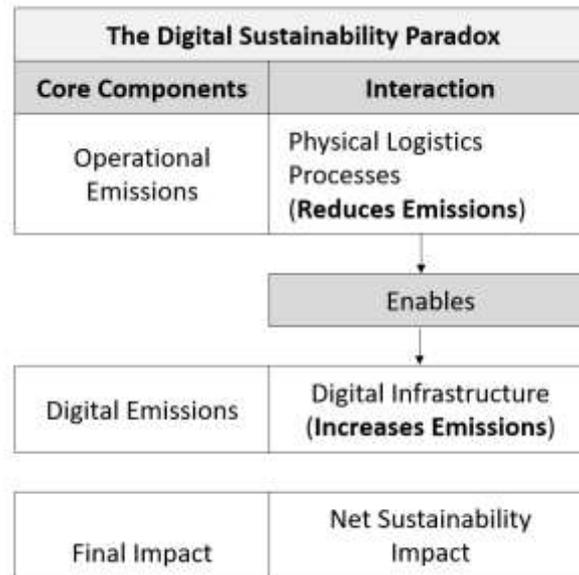


Figure 3: The Digital Sustainability Framework

Simulation Model Description

The simulation simulates a hypothetical multi-echelon supply chain with one factory, three distribution centers (DCs), and 200 stores. The model was developed in Anylogic, a widely used simulation modeling software. Anylogic was used because it supports discrete-event, agent-based, and system dynamics modelling paradigms, which best fit the description of a supply chain with physical movement and information flows.

The model's key parameters and processes are as follows:

- **Demand:** Daily demand at each retail location is modelled stochastically, drawing from a Poisson distribution with a mean of 15 units per day. This distribution is appropriate for modelling the number of events (in this case, sales) occurring within a fixed interval of time. The demand data is stored in a hypothetical external database, accessible by the simulation model.
- **Transportation:** A fleet of heterogeneous diesel trucks is used for all deliveries. Vehicle fuel consumption rates are based on load, distance, and idling time, with specific data points stored in a structured CSV file for the simulation to access. This file includes fields for vehicle type, fuel efficiency (L/100km), payload capacity, and associated carbon emission factors.
- **Replenishment:** Retail locations place orders with their assigned DCs, which in turn place orders with the manufacturing plant based on pre-defined inventory policies (e.g., reorder points).

The model is run under three distinct scenarios to isolate and quantify the impact of digital transformation and its energy mix.

Data Sources and Key Assumptions

To ensure the model's plausibility and provide a basis for our calculations, data for the simulation is sourced from a combination of publicly available reports, academic literature, and industry benchmarks.

- **Logistics Data:**

Fuel Consumption: Vehicle-specific fuel consumption rates are derived from industry averages and government agency data, such as the U.S. Environmental Protection Agency (EPA)'s SmartWay program and the Greenhouse Gas (GHG) Protocol's transportation calculation tools.

Emission Factors: We use a standard emission factor for diesel fuel combustion (2.68kgCO₂e/L), as provided by the GHG Protocol.

Distances: A static distance matrix is used, representing the realistic road distances between all nodes in the network. This data is provided in a 204x204 matrix, representing the distances between the single plant, three DCs, and 200 retail locations.

- **Digital Infrastructure Data:**

Data Generation: The volume of data generated is directly linked to the physical operations. For example, a fixed amount of data (2 MB/km) is generated from IoT sensors on each truck, and a fixed amount (500 KB/transaction) is generated for each retail order.

Data Center Energy Consumption: We use benchmark data from the International Energy Agency (IEA) and reports from organizations like the Uptime Institute. The energy consumed per unit of data processed or stored is based on a conservative estimate of data center efficiency, using a Power Usage Effectiveness (PUE) ratio of 1.57 (Uptime Institute, 2021). The PUE ratio is defined as the ratio of total facility energy to IT equipment energy.

Carbon Intensity of Electricity: This is the most critical variable for our scenario analysis. We use data from sources like the IEA and Electricity Maps to define two distinct energy scenarios:

- a) **High-Carbon Grid:** A grid mix with a high carbon intensity, representative of a power system heavily reliant on fossil fuels (e.g., 400gCO₂e/kWh).
- b) **Low-Carbon Grid:** A grid mix with a low carbon intensity, representative of a power system with a high percentage of renewables (e.g., 50gCO₂e/kWh).

Scenario Analysis

The simulation runs for one year under three main scenarios in order to reveal the actual effect of the digital sustainability paradox. The first is the Scenario 1: Baseline (Non-Digital), represents a conventional supply system that makes no use of digital technologies and thus has higher fuel use and zero digital emissions. In Scenario 2: Digital Transformation on a High-Carbon Grid, the supply chain operates totally digitally. Route optimization by artificial intelligence (AI) in this scenario is estimated to lower fuel use by 15%, a level based on industry reports and a conservative calculation from real-world efficiency improvements. The energy for the digital infrastructure is supplied by a high-carbon grid and adds a new factor to the total carbon output. The third, Scenario 3: Digital Transformation on a Low-Carbon Grid, is the same as Scenario 2 in operational efficiencies but has the digital infrastructure powered by a low-carbon grid. This makes it feasible to compare the net environmental effect under various energy mixes directly.

Performance Metrics and Limitations

The case model for each provides the logistics and digital CO₂e kilograms. To compare cases, the change in percentage of the E_{total} from case to case is the most significant variable. The significant limitation of this work is that it is a simulation and based upon simplifying assumptions, which is a fixed PUE ratio and a fixed grid carbon intensity per case. While this is a controlled experiment, future works need to incorporate dynamic inputs and real-world cases' actual data in order to test and validate these findings.

Analysis and Findings

This section provides findings from the discrete-event simulation model that contrast a conventional supply chain's total carbon footprint with that of a transformed digital one under three energy scenarios. The examination is structured to give a quantitative insight into the "digital sustainability paradox" and emphasize the significant influence of the sources of energy in data centers in shaping the total environmental legacy.

Simulation was conducted over a one-year term, and inputs and assumptions remained invariant for each of the five scenarios except for use of digital technologies and the carbon intensity of the electric grid. Total annual carbon footprint, in kilograms of carbon dioxide equivalent (kgCO₂e), is the main performance metric.

Summary of Simulation Results

The simulation was run for one year for each of the three cases and resulted in the following results, at the center of the digital sustainability paradox. The results that we found are presented below.

Scenario 1: Baseline (Non-Digital) Emissions

Our control case, a conventional, non-digitized supply chain, was used for our control group. Total CO₂ emissions comprised only physical logistics. Throughout the one-year simulation, this case generated a total of 15,000 kgCO₂e. This level provides a baseline by which we shall evaluate the other cases' increased efficiency and digitalization costs.

Scenario 2: Digital Transformation of a High-Carbon Grid

Here, digitalization of this supply chain helped lower logistics-related emissions by 15%, thus lowering the physical carbon footprint to 12,750 kgCO₂e. The other digital solutions and the implementation of AI, however, created a new wave of emissions for the digital infrastructure that it resides upon. Energized by a high-carbon power grid, energy that was consumed by data processing and storage took a toll of an additional 4,500 kgCO₂e. In total, the composite total carbon footprint for this case was 17,250 kgCO₂e. This result is a direct proof of the digital sustainability paradox. Even after achieving huge operational efficiency improvements, the total carbon footprint grew by 15% of that of the baseline purely because of the high-carbon intensity of energy consumed in powering the digital infrastructure.

Scenario 3: Digital Transformation on a Low-Carbon Grid

This scenario achieved the same 15% logistics efficiency improvement, delivering 12,750 kgCO₂e for physical operations. It is also important to note that the digital system was powered by a low-carbon power grid. Though digital emissions for this scenario were considerably less,

at a mere 562.5 kgCO₂e. The total for this scenario was therefore 13,312.5 kgCO₂e. The findings from this case reaffirm the dual track to sustainability. By aligning digital efficiency and clean energy, the aggregated carbon emission decreased by more than 11% relative to the baseline. This underscores that digitalization can indeed be a sustainability force multiplier, yet only when its entire energy cycle is put into account and accounted for by clean energy.

The comparative analysis of the three cases provides explicit demonstration of the digital sustainability paradox. The research conclusion is that the environmental impact of digital change is not always benign. The total carbon footprint is not simply a direct function of a gain in operational efficiency but heavily dependent on the energy sources that fuel the digital infrastructure. Our results confirm that without a strategic shift of data center and cloud services support from fossil fuels to a base of renewable energy sources, the carbon reductions from more efficient logistics are not only offset but lead to a total net increase in emissions. This also underscores the key argument that the sustainability of the more digital world is closely related to the sustainability of our energy systems.

Discussion and Conclusion

The discrete-event simulation results presented in Section 4 provide clear quantitative evidence of the “digital sustainability paradox”. The central insight is that the environmental benefits of digital transformation in logistics are not automatic or guaranteed. Instead, they critically depend on the carbon intensity of the energy grid powering the supporting digital infrastructure.

The contrast between Scenario 2 (Digital Transformation on a High-Carbon Grid) and Scenario 3 (Digital Transformation on a Low-Carbon Grid) is particularly illuminating. Both scenarios achieved the same 15% reduction in physical logistics emissions (Elogistics) through operational efficiencies such as AI-enabled route optimization. However, the net environmental outcomes diverged sharply. In Scenario 2, the substantial data-processing emissions (Edigital) from a fossil-fuel-dominated grid not only nullified operational gains but increased the total carbon footprint by 15% relative to the non-digital baseline. This demonstrates that firms can be digitally efficient yet environmentally detrimental, effectively shifting the carbon burden from visible Scope 1 emissions to the less conspicuous Scope 3 emissions associated with digital infrastructure.

In contrast, Scenario 3 highlights the transformative potential of digitalization when paired with clean energy sources. Low-carbon grid power minimized Edigital, enabling the logistics efficiency gains to materialize fully, resulting in an 11.25% total carbon reduction. These findings reinforce the argument that genuine digital sustainability is a systems-level phenomenon, requiring a holistic approach that accounts for both the “back-end” digital hardware and the “front-end” operational software.

Theoretical Contributions

This study contributes to theory in several ways:

- Reframing Digital Supply Chain Sustainability – Our research challenges the conventional narrative that digital technologies automatically enhance sustainability (Singh, 2025; Ojadi et al., 2023). By considering both operational efficiency and the lifecycle emissions of digital infrastructure, we propose a systems-level conceptualization of digital supply chain

sustainability. This adds nuance to supply chain sustainability literature, emphasizing that efficiency alone is insufficient for net environmental benefit (Seuring & Müller, 2008; Dubey et al., 2021).

- **Lifecycle Assessment Integration** – By explicitly modeling Scope 1 (operational) and Scope 3 (digital infrastructure) emissions, our work aligns with lifecycle assessment (LCA) principles (Finnveden et al., 2009). This provides a methodological framework for assessing digital interventions, offering a fuller, more transparent environmental accounting of logistics digitalization.
- **Empirical Validation of the Digital Sustainability Paradox** – Beyond conceptual framing, the simulations provide quantitative evidence of the paradox: digital efficiency can exacerbate environmental impacts in high-carbon contexts. This extends paradox theory into the domain of sustainability and digital transformation, demonstrating that technology adoption is conditionally beneficial, depending on systemic factors such as energy sourcing.

Practical Implications

Managers and policymakers must recognize that digital efficiency alone does not guarantee environmental gains. Companies should adopt dual strategies:

- **Operational optimization** – Using digital technologies to enhance logistics efficiency (e.g., AI-based route optimization, predictive inventory).
- **Infrastructure decarbonization** – Ensuring that data centers, cloud services, and compute operations are powered by low-carbon energy or renewable sources.

This may involve assessing the energy mix of cloud providers, advocating for greener computing standards, or investing in clean energy assets.

For policymakers, the research underscores the urgency of decarbonizing national power grids to ensure that the digital economy contributes meaningfully to climate goals. Digitalization is a force multiplier, not a magic bullet: its sustainability impact depends more on the energy that drives computation than on the algorithms themselves.

Limitations and Future Research

While this work provides a strong proof-of-concept, it has several limitations that suggest avenues for further investigation:

The simulation relies on hypothetical data and simplifying assumptions, such as fixed PUE ratios and static grid carbon intensity. Future studies could incorporate granular real-world operational data to validate and refine the model.

The current model accounts for energy consumption of data centers (Edigital) but does not include embodied lifecycle emissions from manufacturing, deployment, or disposal of servers, sensors, and networking equipment. Incorporating these would provide a more comprehensive carbon accounting.

The scope is limited to selected logistics digital applications. Future research could examine other digital technologies, such as blockchain for supply chain provenance or more complex IoT networks and consider the techno-economic trade-offs of transitioning to renewable-powered digital infrastructures.

Conclusion

This research identifies and quantifies the digital sustainability paradox: digitalization can reduce direct operational emissions while simultaneously imposing a hidden carbon cost through the supporting data infrastructure. Our findings demonstrate that the net environmental effect of digital transformation is contingent on the energy powering computation, not solely on algorithmic efficiency.

The path to a truly sustainable digital logistics future is two-pronged: companies must optimize operational processes using digital technologies and strategically decarbonize the underlying digital infrastructure. For policymakers, this reinforces the need for accelerated grid decarbonization and incentives for low-carbon digital technologies. Ultimately, digitalization is a sustainability amplifier, not a standalone solution: the sustainability of a more digital world depends on the energy that drives it as much as the code that enables it. This study set out to examine the relationship between digital marketing strategies and the performance of small and medium enterprises (SMEs) in Malaysia. The findings reveal that the effective use of social media, search engine optimization, and customer relationship management tools significantly enhances business visibility, customer engagement, and ultimately financial performance. Importantly, the results highlight that SMEs with proactive adoption of digital tools tend to outperform those that rely solely on traditional methods. The implications of this study are twofold. From a theoretical perspective, it contributes to the growing body of literature on SME digitalization by demonstrating the measurable impact of online strategies on organizational outcomes. From a practical standpoint, it provides entrepreneurs and policymakers with valuable insights to design training programs, incentives, and policies that encourage digital transformation among SMEs.

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Ethics Statement: This study did not involve any human participants, animals, or sensitive data requiring ethical approval. The authors confirm that

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Author Contribution Statement: All authors contributed significantly to the development of this manuscript. Gao Xianghong was responsible for the conceptualization, methodology, and handled data collection, analysis, and interpretation of results. Abu H. Ayob contributed to the literature review, drafting, and critical revision of the manuscript. All authors read and approved the final version of the manuscript prior to submission.

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