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AI-Enabled Digital Twins for Low-Carbon Logistics in Emerging Markets: A Human-Centric Framework for Cold-Chain Energy Efficiency and CBAM-Ready Supply Chains in India "A Human-Centric Framework for Energy-Efficient and Sustainable Cold-Chain Supply Chains"

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Abstract
Cold-chain logistics play a critical role in ensuring food security and pharmaceutical safety in emerging markets; however, they remain among the most energy-intensive and environmentally sensitive segments of modern supply chains. In countries such as India, rapid expansion of cold-chain infrastructure has been accompanied by persistent challenges related to refrigeration energy inefficiency, product spoilage, fragmented decision-making, and limited carbon transparency. At the same time, evolving global sustainability expectations and carbon-linked trade mechanisms are increasing the need for reliable, auditable emission information across logistics operations. This paper proposes a human-centric, AI-enabled digital twin framework aimed at improving energy efficiency, reducing carbon intensity, and enhancing sustainability transparency in food and pharmaceutical cold-chain logistics within emerging markets. Adopting a conceptual design-science approach, the study integrates insights from cold-chain engineering, logistics management, artificial intelligence, and sustainability governance. A layered digital twin architecture is developed that combines real-time operational data, energy-aware system modelling, AI-driven optimization, and human-in-the-loop decision support. Illustrative energy and emission calculations are presented to demonstrate potential reductions in refrigeration energy demand, spoilage risk, and operational uncertainty. The proposed framework emphasizes human accountability and explainable AI, ensuring that technological intelligence augments rather than replaces managerial judgment. By linking operational optimization with sustainability reporting and future carbon compliance readiness, the framework offers practical value for logistics managers, exporters, and policymakers. The study contributes a structured pathway for transforming cold-chain logistics into an energy-efficient, transparent, and future-ready system capable of supporting sustainable growth in emerging markets.

Keywords: Digital Twin, Cold-Chain Logistics, Energy Efficiency, Artificial Intelligence in Logistics, Human-Centric Decision Support, Carbon Transparency, Emerging Markets, Sustainable Supply Chains

Introduction
Context and Motivation
Cold-chain logistics constitute a critical component of modern supply chains, particularly in emerging markets where they support food security, public health, and export competitiveness. Temperature-controlled storage and transportation systems are essential for preserving the quality of perishable agricultural products and ensuring the safety and efficacy of pharmaceutical goods. In countries such as India, rapid economic growth, urbanization, and integration into global

trade networks have accelerated the expansion of cold-chain infrastructure across food and pharmaceutical sectors. Despite their strategic importance, cold-chain logistics systems are inherently energy-intensive. Continuous refrigeration requirements, exposure to high ambient temperatures, frequent loading and unloading operations, and long transport distances collectively contribute to significant electricity and fuel consumption. In many cases, logistics operators rely on conservative operating practices—such as maintaining lower-than-necessary temperature set points—to avoid product spoilage or regulatory non-compliance. While these practices enhance safety margins, they often result in excessive energy use, higher operating costs, and increased carbon emissions. At the same time, sustainability considerations are increasingly influencing how supply chains are evaluated and governed. Environmental performance is no longer viewed solely as a corporate social responsibility objective; it has become a determinant of market access, investor confidence, and long-term competitiveness. Emerging markets now face growing expectations to demonstrate transparency and accountability in supply-chain emissions, particularly for export-oriented industries. These pressures are expected to intensify as carbon-linked trade mechanisms and disclosure requirements evolve globally. Within this context, cold-chain logistics occupy a critical intersection between operational efficiency and sustainability performance. Improving energy efficiency in refrigeration-based logistics can yield multiple benefits, including cost reduction, emission mitigation, reduced product losses, and enhanced resilience. However, achieving these outcomes requires more than incremental technological upgrades; it demands integrated systems capable of supporting informed, real-time decision-making across complex logistics networks.

Problem Statement

Despite advances in digitalization and automation, most cold-chain logistics systems in emerging markets continue to operate in a fragmented and reactive manner. Data related to temperature control, energy consumption, route conditions, and asset performance are often collected in isolation, if at all. As a result, decision-making relies heavily on operator experience and predefined rules rather than holistic system-level insights. Existing digital tools commonly address individual aspects of logistics operations, such as route planning, basic temperature monitoring, or fleet management. While these tools provide incremental improvements, they do not offer an integrated view that links physical system behaviour, energy performance, and environmental impact. Consequently, energy inefficiencies remain largely invisible, and opportunities for optimization are missed. Moreover, the absence of transparent and traceable emission data limits the ability of organizations to assess their sustainability performance or prepare for future compliance requirements. Another critical limitation lies in the growing reliance on automated optimization and artificial intelligence systems that operate as opaque decision engines. In safety-critical environments such as food and pharmaceutical cold chains, a lack of explain ability and human oversight can undermine trust, accountability, and adoption. Fully automated systems may optimize narrow objectives without adequately accounting for human judgment, operational constraints, or ethical considerations. These challenges highlight a fundamental gap: the lack of an integrated, human-centric system that connects cold-chain operations, energy efficiency, intelligent optimization, and sustainability transparency within a unified framework tailored to emerging market conditions.

Research Gap

Current research on cold-chain logistics, digital twins, artificial intelligence, and sustainable supply chains has progressed largely along parallel paths. Engineering-focused studies emphasize refrigeration performance and thermal efficiency, while logistics and management research concentrates on cost, service levels, and coordination. Separately, digital twin and AI-based approaches have demonstrated potential for simulation and optimization, primarily in manufacturing and high-income market contexts.

However, limited attention has been given to the integration of these domains in the context of emerging markets. Specifically, there is a lack of frameworks that simultaneously:

- Model cold-chain thermal and energy behaviour,
- Leverage AI for predictive and adaptive optimization,
- Preserve human oversight and accountability in decision-making, and
- Support transparency and readiness for evolving carbon accountability mechanisms.

As a result, existing approaches fall short of addressing the combined operational, environmental, and governance challenges faced by cold-chain logistics systems in emerging economies.

Objectives and Contributions

The primary objective of this paper is to develop a human-centric, AI-enabled digital twin framework that enhances energy efficiency and sustainability transparency in cold-chain logistics within emerging markets. Using India as a representative context, the study seeks to bridge the gap between engineering efficiency and managerial decision-making.

The key contributions of this paper are as follows:

- It proposes an integrated digital twin architecture explicitly focused on cold-chain energy performance.
- It embeds AI-based optimization within a human-in-the-loop governance structure to ensure explain ability and accountability.
- It introduces illustrative models and calculations to demonstrate potential reductions in energy consumption,

spoilage risk, and operational uncertainty.
- It links operational optimization with sustainability reporting and future carbon compliance readiness, offering practical relevance for logistics managers and policymakers.

Paper Organization

The remainder of this paper is organized as follows. Section 2 presents a comprehensive review of relevant literature on cold-chain logistics in emerging markets, digital twins, artificial intelligence applications in supply chains, and carbon transparency considerations. Section 3 describes the research methodology adopted in the study, including the conceptual design-science approach and key assumptions. Section 4 introduces the proposed human-centric AI-enabled digital twin framework and explains its layered architecture and governance mechanisms. Section 5 presents illustrative models and calculations to analyse refrigeration energy consumption, transport emissions, and spoilage-related risks within cold-chain operations. Section 6 demonstrates the application of the proposed framework through a representative Indian food and pharmaceutical cold-chain mini case. Section 7 discusses the expected results, stakeholder impacts, managerial implications, and future research directions. Finally, Section 8 lists the references used in the study.

Background and Literature Review

Cold-Chain Logistics in Emerging Markets

Cold-chain logistics play a vital role in supporting food security, public health, and export-oriented growth in emerging markets. These systems encompass temperature-controlled storage, transportation, and handling processes designed to preserve product quality from production to consumption. In countries such as India, cold-chain infrastructure has expanded rapidly in response to rising demand for perishable food products, pharmaceuticals, and vaccines. Government initiatives, private investments, and increasing participation in global trade have further accelerated this growth. Despite this expansion, cold-chain logistics in emerging markets continue to face structural challenges. Infrastructure is often fragmented, with significant variation in technology adoption, maintenance standards, and operational practices across regions and operators. Small and medium-sized enterprises dominate much of the cold-chain sector, frequently operating with limited access to advanced monitoring systems or energy management tools. As a result, refrigeration assets are often underutilized or operated conservatively to compensate for uncertainty, leading to higher energy consumption and operating costs. Additionally, emerging markets experience climatic conditions that intensify cold-chain energy demand. High ambient temperatures, humidity, and unreliable power supply increase thermal loads and necessitate backup systems, such as diesel generators, further raising emissions. These challenges highlight the need for solutions that are technically robust, economically feasible, and adaptable to diverse operating environments.

Energy Consumption and Spoilage Dynamics in Cold Chains

Energy consumption in cold-chain logistics is driven primarily by refrigeration processes, which must operate continuously to maintain safe temperature ranges. Thermal losses occur through multiple pathways, including heat transfer through insulation, air infiltration during loading and unloading, and internal heat generated by equipment and product respiration. In transport operations, additional energy is consumed by vehicle propulsion and auxiliary refrigeration units, often powered by fossil fuels. A central challenge in cold-chain management is the trade-off between energy efficiency and spoilage risk. To avoid temperature excursions that could compromise product quality or regulatory compliance, operators frequently adopt conservative strategies such as lower set points and extended cooling cycles. While effective in reducing spoilage, these practices can significantly increase energy use and emissions. Conversely, aggressive energy-saving measures without adequate monitoring or predictive control can elevate the risk of product loss, particularly in pharmaceutical logistics where temperature deviations are tightly regulated. The lack of integrated tools to quantify and balance these competing objectives often leads to suboptimal outcomes. Energy inefficiencies remain hidden, spoilage risks are managed reactively, and opportunities for improvement are identified only after failures occur. This dynamic underscores the importance of decision-support systems capable of linking thermal behaviour, energy consumption, and quality outcomes in real time.

Digital Twins in Logistics and Industrial Systems

Digital twins have emerged as a powerful concept for representing and managing complex physical systems through dynamic virtual models. By continuously synchronizing with real-time data, digital twins enable simulation, diagnostics, and predictive analysis across a wide range of industrial applications. In logistics, digital twins have been used to model supply-chain flows, asset utilization, and operational resilience, particularly in high-income and technologically mature contexts. In cold-chain logistics, digital twins offer significant potential to capture the thermal and operational behaviour of refrigeration systems, transport routes, and storage facilities. Through scenario analysis, digital twins can evaluate the impact of alternative operating strategies, such as route changes or set point adjustments, before implementation. However, existing applications often prioritize delivery performance and asset reliability, with limited emphasis on energy-centric modelling or sustainability outcomes. Moreover, many digital twin implementations treat the virtual model as a technical artefact, separate from human decision-making processes. This separation limits their effectiveness in environments where operator judgment, contextual knowledge, and accountability are essential. As a result, the full potential of digital twins to support energy-efficient and human-centric logistics decisions remains underutilized in emerging markets.

Artificial Intelligence in Supply Chain Optimization

Artificial intelligence has become an integral component of modern supply chain management, offering advanced capabilities for pattern recognition, prediction, and optimization. In logistics, AI techniques are widely applied to route planning, demand forecasting, inventory optimization, and predictive maintenance. These applications have demonstrated tangible benefits in reducing costs, improving service levels, and enhancing operational reliability. In cold-chain contexts, AI can analyse large volumes of sensor and operational data to identify inefficiencies, predict equipment failures, and recommend optimal operating strategies. For example, machine learning models can forecast refrigeration energy demand under varying ambient conditions or detect early signs of insulation degradation. Despite these advantages, AI-driven systems often operate as opaque "black boxes," generating recommendations without sufficient explanation of underlying reasoning. This lack of transparency poses challenges for adoption, particularly in safety-critical logistics environments. Operators may be reluctant to rely on recommendations they do not fully understand, while managers may struggle to assign accountability for automated decisions. These concerns highlight the importance of integrating AI within governance structures that prioritize explain ability, human oversight, and trust.

Carbon Transparency and Emerging Compliance Pressures

Carbon transparency has become an increasingly important dimension of supply-chain management. Organizations are under growing pressure to quantify and disclose emissions associated with their operations, driven by regulatory requirements, investor expectations, and customer demand. For emerging markets, these pressures are amplified by their role in global supply chains, where downstream partners often impose sustainability standards. Cold-chain logistics contribute significantly to supply-chain emissions due to their reliance on energy-intensive refrigeration and fuel-based transport. However, emission data from these operations are frequently incomplete, inconsistent, or estimated using coarse assumptions. This lack of reliable data limits the ability of organizations to assess their environmental impact or evaluate improvement strategies. As carbon accountability mechanisms evolve globally, the need for traceable, auditable emission information is expected to increase. Preparing for such requirements requires systems that can integrate operational data with sustainability metrics, enabling organizations to move from ad hoc reporting toward continuous, data-driven transparency.

Positioning Against Existing Frameworks

Existing logistics optimization frameworks typically focus on cost efficiency, delivery time, or asset utilization. While these objectives are important, they often overlook energy performance, human governance, and sustainability transparency. AI-only optimization approaches may enhance efficiency but frequently lack explain ability and structured accountability. Conversely, sustainability reporting tools often operate independently of operational decision-making, limiting their practical impact. The framework proposed in this paper differs by explicitly integrating cold-chain energy modelling, AI-enabled optimization, human-in-the-loop governance, and carbon transparency within a unified system architecture. This integrated approach is particularly suited to emerging markets, where resource constraints, operational variability, and governance considerations demand adaptable and transparent solutions.

Dimension	Traditional Logistics Tools	AI-only Optimization	Proposed AI–DT Framework
Energy modelling	Low	Medium	***High (explicit)***
Cold-chain focus	Partial	Partial	***Explicit***
Human oversight	Manual	Limited	***Central***
Explain ability	Low	Low–Medium	***High***
Carbon transparency	Weak	Emerging	***Integrated***

Table 1: Comparison of Existing Approaches Vs Proposed Framework

Research Methodology

Research Approach

This study adopts a conceptual design-science research approach to address the complex and interdisciplinary challenges associated with energy efficiency and sustainability in cold-chain logistics. Design-science methodology is particularly suitable for problems where practical relevance, system integration, and decision support are central, and where empirical implementation may be constrained by cost, data availability, or organizational barriers. Rather than testing a single technology in isolation, the approach focuses on developing a structured framework that integrates multiple technological and human elements into a coherent system. The research is grounded in the recognition that cold-chain logistics in emerging markets represent socio-technical systems, where physical infrastructure, digital technologies, and human decision-making interact dynamically. Consequently, the methodology emphasizes system design and conceptual validation rather than purely analytical or statistical evaluation.

Methods Employed

The study employs a multi-stage methodological process comprising the following components:

Structured Literature Synthesis

A structured review of academic literature, policy documents, and industry reports was conducted to identify prevailing trends, challenges, and gaps related to:

- Cold-chain logistics and refrigeration energy consumption,
- Digital twin applications in logistics and industrial systems,
- Artificial intelligence in supply-chain optimization, and
- Carbon transparency and sustainability governance.

The synthesis focused on extracting conceptual insights rather than replicating empirical findings, enabling the development of a framework that reflects both theoretical understanding and practical constraints in emerging markets.

Conceptual Framework Design

Building on insights from the literature, a layered human-centric AI-enabled digital twin framework was developed. The framework design process involved:

- Identifying key physical and digital components of cold-chain systems,
- Defining data flows between physical assets, digital twins, and AI analytics,
- Incorporating human decision points and governance mechanisms, and
- Aligning operational outputs with sustainability and transparency objectives.

This design phase emphasized modularity and adaptability, ensuring that the framework can be scaled and customized across different cold-chain contexts and organizational sizes.

Illustrative Modelling and Analytical Demonstration

To demonstrate the practical relevance of the proposed framework, illustrative energy and emission calculations were developed. Simplified thermodynamic and energy balance models were used to estimate refrigeration energy demand under baseline and optimized scenarios. These models are not intended to represent exact operational conditions but to illustrate how digital twins and AI-driven insights can influence energy performance and decision-making. In addition, a representative cold-chain logistics scenario was formulated to contextualize the framework within an Indian food and pharmaceutical supply chain. Scenario-based analysis enables exploration of system behaviour under alternative operating strategies without requiring access to proprietary or large-scale datasets.

Scope and Assumptions

The scope of this study is intentionally defined to support conceptual clarity and generalizability. The analysis focuses on temperature-controlled logistics for food and pharmaceutical products within emerging market contexts, with India serving as a representative case. The framework emphasizes system-level integration rather than detailed component-level optimization.

Several assumptions are made for illustrative purposes:

- Refrigeration systems operate within typical performance ranges reported in the literature,
- Energy and emission factors are represented using standard proxy values,
- And human operators retain final decision authority over AI-generated recommendations.

These assumptions do not limit the applicability of the framework but provide a transparent basis for conceptual demonstration.

Methodological Validity and Relevance

The chosen methodology aligns with the objectives of this study by balancing academic rigor with practical relevance. Conceptual design-science approaches are widely accepted in logistics and sustainability research, particularly when addressing emerging technologies and system-level challenges. By combining literature synthesis, framework design, and illustrative modelling, the methodology supports the development of actionable insights while avoiding over-generalization or unwarranted empirical claims. Importantly, the methodology reflects the human-centric philosophy underlying the proposed framework. By explicitly accounting for human oversight, explain ability, and governance, the research approach acknowledges that sustainable transformation in cold-chain logistics requires both technological innovation and informed human judgment.

Proposed Human-Centric AI–Digital Twin Framework

Framework Overview

The proposed framework is designed to transform cold-chain logistics from a reactive, energy-intensive operation into a predictive, energy-aware, and transparent system. At its core, the framework integrates physical cold-chain assets with digital intelligence while preserving human oversight and accountability. Rather than viewing technology as a replacement for human decision-makers, the framework positions artificial intelligence and digital twins as decision-support tools that enhance situational awareness and operational judgment. The framework follows a layered architecture that connects real-time operational data, system-level simulation, AI-driven optimization, and sustainability reporting within a unified structure. This architecture enables continuous feedback between physical operations and digital models, allowing logistics stakeholders to evaluate the energy, quality, and environmental implications of alternative decisions before implementation.

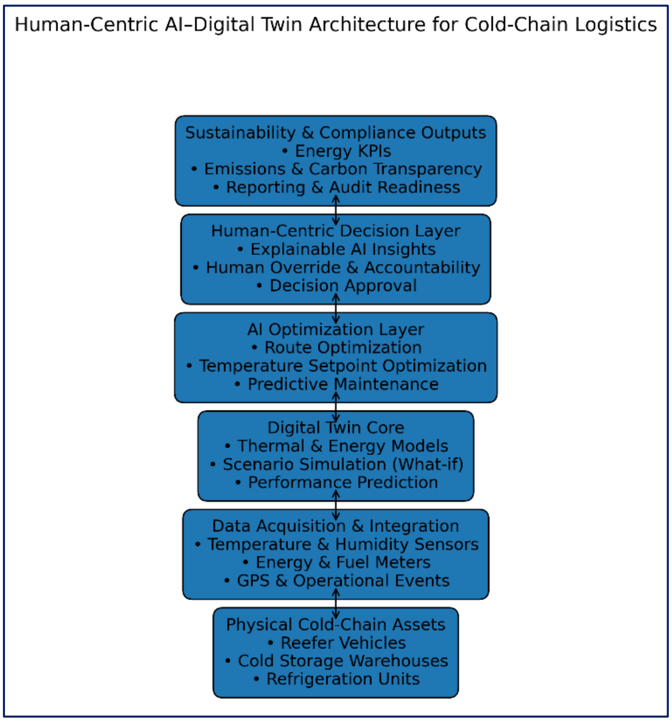

Figure 1: Human-Centric AI–Digital Twin Architecture

Physical Cold-Chain Asset Layer

The foundation of the framework consists of physical cold-chain assets, including refrigerated transport vehicles, cold storage warehouses, and refrigeration units, packaging systems, and handling equipment. These assets determine baseline energy demand and directly influence product quality and safety. In food and pharmaceutical logistics, variability in load composition, ambient temperature, and operational practices results in highly dynamic thermal behaviour. Within the proposed framework, physical assets are treated not merely as isolated components but as interconnected elements of a system whose performance depends on coordinated operation. Recognizing this interdependence is essential for identifying energy inefficiencies that arise from suboptimal interactions between transports, storage, and handling processes.

Data Acquisition and Integration Layer

The data acquisition layer captures operational and environmental information necessary for constructing an accurate digital representation of the cold chain. Typical data streams include temperature and humidity readings, refrigeration power consumption, fuel usage, vehicle location, door-opening events, and load factors. These data are collected through sensors, telemetry systems, and existing logistics management platforms. A critical function of this layer is data integration and synchronization. Cold-chain operations generate heterogeneous data at different temporal and spatial resolutions. Aligning these data streams through time-stamping, validation, and filtering ensures consistency and reliability for downstream analysis. By consolidating fragmented information into a unified dataset, the framework enables system-level insights that are otherwise unavailable through isolated monitoring tools.

Digital Twin Core

The digital twin core forms the analytical backbone of the framework. It represents a dynamic virtual model of the physical cold-chain system, continuously updated using real-time and historical data. Unlike static simulation models, the digital twin evolves with operational conditions, enabling near-real-time assessment of system behaviour. Within the cold-chain context, the digital twin incorporates thermal models of refrigeration systems, heat ingress through insulation, route-time relationships, and load variations. These models allow the simulation of "what-if" scenarios, such as changes in delivery routes, temperature set points, or maintenance schedules. By quantifying the energy and quality implications of alternative strategies, the digital twin supports proactive decision-making rather than reactive problem-solving. Importantly, the digital twin is designed with an explicit energy-first perspective. While traditional logistics models prioritize time and cost metrics, the proposed twin foregrounds energy consumption, refrigeration performance, and associated emissions as primary performance indicators.

AI-Driven Optimization Layer
Artificial intelligence enhances the capabilities of the digital twin by enabling predictive and adaptive optimization. AI algorithms analyse patterns in historical and real-time data to forecast energy demand, detect anomalies, and recommend optimal operating strategies. In cold-chain logistics, such applications include route optimization that accounts for ambient temperature and traffic conditions, predictive maintenance of refrigeration components, and adaptive control of temperature set points. The AI layer does not operate independently; instead, it draws inputs from the digital twin and feeds outputs back into the simulation environment. This closed-loop interaction ensures that AI recommendations are grounded in physical system behaviour rather than purely statistical correlations. As a result, optimization outcomes are more robust and context-aware.

Edge Computing and Data Resilience
To address the realities of intermittent connectivity in emerging markets, the proposed framework supports edge-level data processing and buffering. Local edge devices can perform preliminary data aggregation, rule-based monitoring, and anomaly detection during periods of network disruption. Once connectivity is restored, buffered data are synchronized with the central digital twin. This hybrid edge–cloud architecture enhances operational resilience and ensures continuity of monitoring across rural and infrastructure-constrained logistics routes.

Human-Centric Decision Support Layer
A defining feature of the proposed framework is its emphasis on human-centric governance. In safety-critical cold-chain operations, human judgment remains essential for interpreting system recommendations, managing risk, and ensuring accountability. The framework therefore incorporates a decision-support layer that presents AI-generated insights through explainable and intuitive interfaces. These interfaces translate complex analytical outputs into actionable information, such as expected energy savings, spoilage risk implications, and trade-offs between competing objectives. Operators and managers retain the authority to accept, modify, or override AI recommendations based on contextual knowledge and operational constraints. By maintaining humans "in the loop," the framework fosters trust, reduces automation bias, and supports responsible decision-making.

Governance, Accountability, and Decision Rights
Effective deployment of advanced digital technologies requires clear governance structures. The proposed framework explicitly defines roles and responsibilities associated with decision-making and system oversight. AI systems are responsible for generating recommendations and forecasts, while human operators and managers are accountable for final decisions and their outcomes. Decision actions and overrides are recorded within the system, creating an audit trail that supports transparency and continuous learning. This governance mechanism ensures that responsibility for safety, quality, and compliance remains clearly assigned, addressing ethical and organizational concerns associated with automation in logistics.

Sustainability and Compliance Output Layer
The final layer of the framework focuses on translating operational data into sustainability-relevant outputs. Energy consumption and fuel usage information are aggregated to estimate emissions and identify carbon hotspots across the cold-chain network. These outputs support internal performance monitoring and provide a foundation for sustainability reporting and future compliance readiness. By embedding sustainability metrics directly within operational decision-support systems, the framework bridges the gap between day-to-day logistics management and long-term environmental objectives. This integration enables organizations to move beyond retrospective reporting toward proactive sustainability management.

Models, Calculations, and Illustrative Analysis
This section presents simplified yet meaningful analytical models and illustrative calculations to demonstrate how the proposed human-centric AI–digital twin framework can influence energy consumption, spoilage risk, and operational efficiency in cold-chain logistics. The objective is not to provide exact operational predictions but to show how integrated modelling and intelligent decision support can guide better-informed logistics decisions.

Refrigeration Energy Modelling in Cold-Chain Systems
Refrigeration energy consumption constitutes the largest share of total energy use in cold-chain logistics. The cooling load required to maintain the desired internal temperature is influenced by heat transfer through insulation, air infiltration during loading and unloading, and heat exchange with the stored products.

The total cooling load can be expressed as:
Cooling load equation:

$$Q_{cool} = U \times A \times (T_{out} - T_{in}) + Q_{product} + Q_{infiltration}$$

Where:
Q_{cool} = total cooling load (kW) U = overall heat transfer coefficient A = effective heat transfer area T_{out} = ambient temperature

T_{in} = internal set temperature
$Q_{product}$ = heat due to product thermal mass
$Q_{infiltration}$ = heat gain due to door opening and air leakage

The electrical power required to operate the refrigeration system is given by:
Electrical power equation:

$$P_{elec} = Q_{cool} / COP$$

Where:
P_{elec} = electrical power input (kW)

COP = coefficient of performance of the refrigeration system The total energy consumed over a duration t is calculated as:
Energy consumption equation:

$$E = P_{elec} \times t$$

Where:
E = energy consumption (kWh) t = operating time (hours)

Illustrative Energy Calculation: Baseline and Optimized Scenarios
To illustrate the effect of AI-enabled digital twin optimization, a representative refrigerated transport operation is considered.
Baseline Scenario Assume:

Q_{cool} = 3.5 kW COP = 2.0

Trip duration, t = 10 hours Electrical power required:

$$P_{elec} = 3.5 / 2.0 = 1.75 \text{ kW}$$

Total energy consumption per trip:

$$E = 1.75 \times 10 = 17.5 \text{ kWh}$$

AI–Digital Twin Optimized Scenario
Using insights from the digital twin and AI-based optimization, operational improvements such as optimized temperature set points and reduced door-opening duration are implemented. These measures reduce the effective cooling load by approximately 15%.

Optimized cooling load:
$Q_{cool, opt}$ = 2.975 kW Optimized electrical power:
$P_{elec, opt}$ = 2.975 / 2.0 = 1.49 kW Optimized energy consumption:
$E_{opt} = 1.49 \times 10 = 14.9$ kWh
Thus, the energy saving achieved is:
Energy saving per trip = 17.5 − 14.9 = 2.6 kWh

Transport Emissions Estimation
In addition to refrigeration energy consumption, fuel usage during transportation contributes significantly to overall emissions. A simplified activity-based approach is used:
Emission estimation equation:
CO_2 emissions = Fuel consumption × Emission factor
This formulation enables comparison of alternative routing and operational strategies within the digital twin environment.

Refrigerant Leakage Acknowledgement Paragraph
It is important to note that the emissions analysis presented in this study primarily focuses on energy-related carbon dioxide emissions associated with electricity and fuel consumption. Refrigerant leakage, which can contribute significantly to overall greenhouse gas emissions due to the high global warming potential of commonly used refrigerants in aging cold-chain assets, is not explicitly quantified in the current model. Incorporating refrigerant leakage monitoring and life-cycle emission accounting within the digital twin represents an important extension of the proposed framework and is identified as a priority for future research.

Spoilage Risk Indicator as a Human-Centric Metric

Product quality and safety are critical outcomes in cold-chain logistics. To represent spoilage risk in a transparent and human-interpretable manner, a Temperature Excursion Index (TEI) is defined.

TEI equation:

$$TEI = \Sigma\ [\max(0, T\_i - T\_safe) \times \Delta t]$$

Where:

T_i = observed temperature at time interval i T_safe = maximum allowable safe temperature Δt = duration of the time interval

Lower TEI values indicate improved temperature compliance and reduced spoilage risk.

Energy–Spoilage Trade-off Analysis

Energy efficiency improvements in cold-chain logistics must be evaluated alongside their impact on product quality. Aggressive energy reduction strategies may inadvertently increase spoilage risk if temperature control is compromised. The digital twin enables visualization of this trade-off by simulating alternative operating strategies and plotting energy consumption against TEI values.

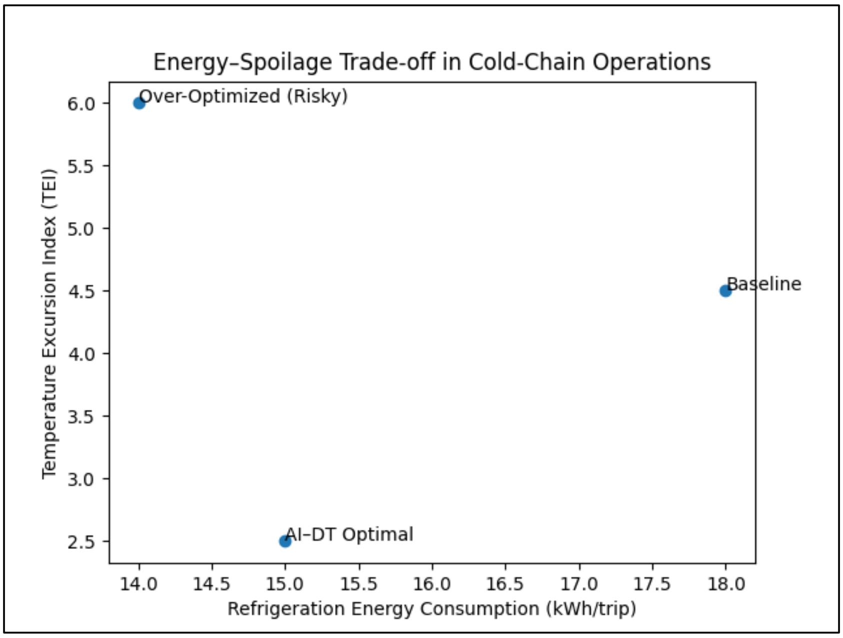

Figure 2: Energy vs Spoilage Trade-off Curve

Indicative Economic Implications

Although the analysis is illustrative, the results indicate meaningful economic benefits. Reduced refrigeration energy consumption lowers electricity or fuel costs, while improved temperature control reduces product losses. Importantly, these benefits are achieved through operational optimization rather than capital-intensive infrastructure upgrades.

Empirical Validation Readiness and Pilot Study Design

While the present study adopts an illustrative and scenario-based modelling approach, the proposed framework is explicitly designed to support empirical validation through pilot-scale implementation. A feasible next step involves collaboration with a refrigerated logistics service provider to deploy the digital twin across a limited fleet of vehicles or a single cold storage facility. Baseline operational data, including refrigeration energy consumption, temperature excursion frequency, fuel usage, and maintenance events, can be collected over a defined observation period and compared against AI–digital twin–assisted operations. Key performance indicators such as energy consumption per trip, Temperature Excursion Index (TEI), and operational downtime would enable longitudinal assessment of real-world performance and support calibration of the proposed models.

Application to Indian Food and Pharmaceutical Cold-Chain (Mini Case)

This section illustrates the practical relevance of the proposed human-centric AI–digital twin framework through a representative cold-chain logistics scenario in the Indian context. The mini case integrates both food and pharmaceutical products, reflecting the mixed-load realities of many emerging market supply chains. The objective is to demonstrate how the framework supports informed decision-making, energy efficiency improvement, and sustainability transparency without requiring extensive proprietary data.

Case Description and Operational Context

The illustrative case considers a regional cold storage facility supplying a combination of temperature-sensitive food products and pharmaceutical goods to an urban distribution centre. The logistics operation involves refrigerated transport over a medium-distance route, characterized by variable traffic conditions, frequent loading and unloading events, and exposure to high ambient temperatures. Food products in the shipment allow moderate temperature variation, while pharmaceutical products require stricter control within defined safety limits. This mixed-load configuration creates operational complexity, as conservative temperature settings are often used to protect pharmaceutical integrity, increasing overall energy consumption. The case therefore represents a realistic challenge faced by Indian cold-chain operators attempting to balance safety, efficiency, and cost.

Digital Twin Initialization and System Representation

The digital twin is initialized using baseline operational data, including vehicle specifications, refrigeration unit performance characteristics, route profiles, ambient temperature patterns, and typical loading schedules. Thermal models within the twin represent heat ingress through insulation, air infiltration during door openings, and product-related thermal loads. By continuously synchronizing with operational data, the digital twin provides a dynamic representation of the cold-chain system. This enables simulation of alternative scenarios, such as modified delivery routes, adjusted temperature set points, or changes in loading practices, prior to physical implementation.

AI-Driven Optimization and Scenario Evaluation

Using inputs from the digital twin, the AI analytics layer evaluates multiple operating scenarios. These include alternative routes that reduce travel time and exposure to high ambient temperatures, as well as adaptive temperature control strategies that account for product-specific tolerance levels. For each scenario, the system estimates refrigeration energy consumption, transport-related emissions, and the Temperature Excursion Index (TEI) as a proxy for spoilage risk. AI-generated recommendations highlight expected trade-offs, such as modest energy savings versus marginal increases in temperature variability. Importantly, these outputs are presented with explanatory context, allowing operators to understand the basis of each recommendation.

Human-In-The-Loop Decision and Operational Adjustment

Consistent with the human-centric philosophy of the framework, final decisions are made by logistics managers and operators. In the mini case, the recommended strategy involves selecting a route with slightly longer nominal distance but lower congestion and reduced stop frequency, combined with refined set point management during stable transport phases. Operators review the AI recommendations alongside predicted energy savings and TEI values. Based on this information and contextual knowledge of delivery constraints, the recommended strategy is approved and implemented. This process illustrates how human judgment and technological intelligence can complement each other to achieve balanced outcomes.

Sustainability and Transparency Outcomes

Following implementation, the framework aggregates operational data to generate sustainability-relevant outputs. Refrigeration energy use and fuel consumption are tracked at the trip level, enabling estimation of associated emissions. These data are stored with time-stamped audit trails, supporting traceability and future reporting needs. The mini case demonstrates how even incremental improvements—such as reduced door-opening duration or improved route selection—can collectively enhance energy efficiency and emission visibility. For export-oriented supply chains, such transparency supports proactive sustainability management and readiness for evolving carbon accountability expectations.

Discussion of Practical Implications

The illustrative application highlights several practical insights. First, integrating food and pharmaceutical logistics within a single digital twin environment allows differentiated control strategies without compromising safety. Second, energy efficiency gains can be achieved through operational refinement rather than capital-intensive infrastructure changes. Third, maintaining human oversight ensures that optimization strategies remain aligned with real-world constraints and ethical considerations. Overall, the mini case underscores the feasibility of deploying the proposed framework in emerging market contexts, where resource constraints, operational variability, and governance considerations necessitate adaptable and transparent solutions.

Results and Discussion

This section presents the expected outcomes derived from the illustrative modelling and mini case application and discusses their implications for cold-chain logistics in emerging markets. While the analysis is conceptual, the results are grounded in realistic operational assumptions and reflect patterns commonly observed in food and pharmaceutical supply chains.

Graph 2 — Scaling Impact of Energy Savings

Scenario-Based Outcomes

The comparison between baseline operations and the AI–digital twin supported scenario indicates consistent improvements across multiple performance dimensions. Illustrative results show a measurable reduction in refrigeration energy consumption per trip, driven primarily by improved set point management, reduced door-opening duration, and better route selection under varying ambient conditions. When aggregated across daily operations and fleet scales, these incremental savings translate into substantial reductions in total energy demand. In addition to energy efficiency, the optimized scenario demonstrates lower temperature excursion values, indicating improved control of product quality and reduced spoilage risk. Importantly, these improvements are achieved without compromising safety requirements, particularly for pharmaceutical products with strict temperature constraints. This outcome underscores the ability of the proposed framework to balance efficiency objectives with quality assurance. Transport-related fuel use and associated emissions also show improvement in the optimized scenario. Although route selection may not always minimize distance, the consideration of congestion, stop frequency, and thermal exposure leads to lower overall energy and emission intensity. This finding highlights the limitations of distance-based optimization and reinforces the value of system-level decision support.

Metric	Baseline Scenario	AI–DT Supported Scenario	Expected Impact
Refrigeration energy (kWh/trip)	17.5	14.9	↓ ~15%
Fuel consumption	High	Moderate	↓
Spoilage risk (TEI)	Moderate	Low	↓
Unplanned downtime risk	Moderate	Low	↓
Emission visibility	Low	High	↑

Table 2: Baseline vs AI–Digital Twin Scenario Outcomes

Interpretation OF Energy–Quality Trade-Offs

A key insight emerging from the analysis is the importance of managing the trade-off between energy consumption and spoilage risk. Traditional cold-chain practices often prioritize safety margins through conservative operating strategies, resulting in excessive energy use. Conversely, energy-focused optimization without adequate safeguards can increase quality risks. The proposed framework demonstrates that this trade-off is not necessarily zero-sum. By integrating thermal modelling, predictive analytics, and human oversight, the system identifies operating regions where both energy consumption and spoilage risk can be reduced simultaneously.

Stakeholder	Key Value Delivered	Pain Point Addressed	Decision Support Enabled
Operators	Predictive insights	Reactive firefighting	Route & set point choice
Managers	Energy transparency	Hidden inefficiencies	Strategic planning
Exporters	Compliance readiness	Emission uncertainty	Carbon reporting
Regulators	Traceability	Limited data	Monitoring & audits
Consumers	Product safety	Quality variability	Reliable cold-chain

Table 3: Stakeholder Benefit Mapping (Human-Centric)

The use of interpretable metrics, such as refrigeration energy per trip and the Temperature Excursion Index (TEI), enables operators to visualize and manage these trade-offs explicitly.

Stakeholder Impact and Human-Centric Value

The results indicate differentiated benefits for key stakeholders across the cold-chain ecosystem. For operators, improved situational awareness and predictive insights reduce reliance on reactive interventions and manual troubleshooting. Managers benefit from enhanced visibility into energy performance and sustainability outcomes, supporting more informed strategic planning. From a broader perspective, improved cold-chain efficiency contributes to reduced product losses, enhanced consumer safety, and lower environmental impact. The inclusion of human-in-the-loop governance mechanisms ensures that these benefits are achieved without eroding accountability or trust. By preserving human agency in decision-making, the framework aligns technological innovation with organizational and ethical considerations.

Managerial Implications

The findings suggest several important implications for logistics managers in emerging markets. First, meaningful efficiency gains can be achieved through operational optimization supported by digital intelligence, rather than solely through capital-intensive infrastructure upgrades. Second, integrating energy metrics into routine decision-making enables organizations to identify hidden inefficiencies and prioritize targeted interventions. Third, the framework supports a gradual transition toward sustainability-oriented logistics management. By embedding energy and emission considerations within daily operations, organizations can move beyond retrospective reporting toward proactive performance management. This capability is particularly valuable for export-oriented supply chains facing increasing sustainability expectations.

Alignment with Sustainability and Transparency Objectives

The proposed framework contributes to sustainability objectives by linking operational data with energy and emission indicators in a traceable and auditable manner. The scenario-based results illustrate how improved data integration and system-level analysis can enhance transparency without imposing excessive reporting burdens. Rather than treating sustainability compliance as a separate administrative task, the framework integrates transparency into the core logistics workflow. This integration supports long-term preparedness for evolving carbon accountability mechanisms and positions organizations to respond effectively to future regulatory and market-driven sustainability requirements.

SME-Oriented Deployment Strategy

Small and medium-sized enterprises constitute the backbone of cold-chain logistics in emerging markets and often face financial, technical, and organizational constraints when adopting advanced digital technologies. To address these challenges, the proposed framework is intentionally modular and supports phased implementation. Initial adoption can focus on low-cost sensing, basic digital twin visualization, and descriptive analytics to deliver immediate operational visibility. More advanced AI-driven optimization and predictive capabilities can be integrated progressively as data availability and organizational maturity improve. This incremental deployment strategy lowers entry barriers while preserving scalability and long-term value creation.

Discussion in Relation to Existing Literature

The results align with prior studies that highlight the potential of digital twins and AI to improve logistics efficiency. However, this study extends existing work by demonstrating the importance of human-centric governance and energy-focused modelling in cold-chain contexts. While previous frameworks often emphasize automation and optimization, the proposed approach emphasizes explain ability, accountability, and adaptability—attributes that are particularly critical in emerging markets. By situating energy efficiency and sustainability transparency within a unified decision-support system, the framework addresses gaps identified in the literature and offers a more holistic approach to cold-chain transformation.

Summary of Key Findings

The results and discussion indicate that a human-centric AI–digital twin framework can:

- Reduce refrigeration energy consumption without compromising product safety,
- Lower spoilage risk through predictive and adaptive control,
- Enhance visibility of energy and emission performance,
- Support informed and accountable decision-making, and
- Align operational efficiency with long-term sustainability objectives.

These findings reinforce the value of integrating technological innovation with human governance in the pursuit of sustainable cold-chain logistics in emerging markets.

Future Scope

Future research will focus on extending the proposed framework through empirical validation, integration of refrigerant leakage emissions, and refinement of AI algorithms under real-world operating conditions. In particular, reinforcement learning-based set-point optimization and predictive maintenance models offer promising avenues for further enhancing energy efficiency and system reliability. Such extensions will strengthen the framework's applicability across diverse cold-chain contexts and support its evolution into a comprehensive decision-support system for sustainable logistics.

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