

A Hybrid Cold-Chain Optimization Framework for Last-Mile Dairy Distribution under Energy Instability: Integrating Formal and Informal Delivery Networks in Urban Nigeria

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ABSTRACT: Last-mile delivery of dairy products in many African cities is constrained less by distance and more by infrastructure vulnerability. In urban Nigeria, disrupted electricity networks, fuel volatility, traffic congestion, and the coexistence of formal and informal distribution actors create systemic inefficiencies in the cold chain. This paper develops a theoretical hybrid optimization framework for last-mile dairy distribution under conditions of energy instability. The framework goes beyond technology-centric approaches. It integrates energy reliability parameters, product thermal decay functions, and dual-network coordination mechanisms. It links formal logistics providers with informal micro-distributors. The study draws on supply chain resilience theory, resource orchestration logic, and perishable inventory modeling. It conceptualizes how energy risk can be embedded directly into routing, inventory positioning, and delivery sequencing decisions. The proposed model presents three interlinked design layers: energy-adaptive cold-chain configuration, dynamic routing under erratic power supply conditions, and formal–informal network synchronization. The paper argues that spoilage minimization and customer satisfaction are not automatically aligned and must be jointly optimized through cost–temperature–time trade-offs. The framework contributes theoretically by reframing energy instability as a decision variable instead of seeing it as an external disturbance and by conceptualizing informal actors as strategic assets rather than operational noise. The study concludes with implications for urban food security, supply chain competitiveness, and sustainable distribution design in infrastructure-constrained economies.

KEYWORDS: cold chain optimization, energy instability, last-mile logistics, informal distribution networks, dairy supply chain, urban Nigeria

1. INTRODUCTION

Cold-chain logistics research has largely been shaped by experiences in infrastructure-stable economies where electricity is reliable, transport networks are predictable, and regulatory enforcement of temperature compliance is consistent. Within such contexts, optimization models typically assume uninterrupted refrigeration, standardized fleets, coordinated retail networks, and measurable adherence to cold-chain protocols. These assumptions have informed decades of vehicle routing models, perishable inventory systems, and service-level optimization studies. However, when transposed into many emerging urban environments, these foundational premises begin to unravel. In cities such as Lagos, Ibadan, and Port Harcourt, the last mile of dairy distribution does not follow a single coordinated channel. Refrigerated trucks share road space with motorcycles transporting insulated coolers packed with ice blocks. Modern cold rooms operate alongside kiosks powered by small generators or improvised solar units. The distribution ecosystem is layered, improvised, and adaptive yet rarely reflected in formal optimization theory.

Energy instability is not a peripheral inconvenience within this environment; it is a defining structural condition. Intermittent grid supply interrupts cold storage cycles, forces distributors to depend on diesel generators with very unstable fuel costs, and compresses delivery windows around unpredictable outage schedules. Temperature management becomes uncertain rather than controlled. A brief outage at a neighborhood hub may accelerate bacterial growth in high-risk dairy products, shortening viable shelf life in ways that are neither linear nor easily reversible. Spoilage risk therefore behaves nonlinearly: a single prolonged interruption can generate disproportionate losses compared to multiple shorter fluctuations. Despite this reality, most optimization models treat energy supply

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as an exogenous backdrop, assumed available, stable, and uniform across geographic zones. Consequently, routing and inventory decisions are optimized against a simplified representation of operational reality.

Compounding the energy challenge is the dual structure of urban dairy distribution networks. There are formal logistics operators on one side. They are equipped with structured fleets, warehousing facilities, and corporate governance systems. However, on the other side are informal distributors, namely, market traders, micro-retailers, and neighborhood shop owners. They jointly represent a significant portion of daily dairy transactions. Although these actors often lack advanced refrigeration infrastructure, but they possess deep market reach, proximity to end consumers, and remarkable adaptability. Their operations are embedded in social relationships and neighborhood demand patterns that formal systems struggle to replicate. Considering the informal segment as peripheral overlooks its functional importance. So, designing models solely around it ignores capital and compliance constraints. Either omission produces incomplete optimization logic.

The coexistence of formal and informal actors under conditions of energy instability creates a layered coordination problem. Formal firms may invest in refrigerated trucks and warehouse backup systems, but product integrity can still be compromised if downstream micro-retailers lack stable power. Conversely, informal traders tend to preserve customer loyalty and ensure rapid product turnover. However, they struggle to maintain temperature thresholds without access to reliable cold storage. Optimization, therefore, cannot be confined to fleet routing or warehouse configuration alone. It must account for the structural interdependence between actors operating under uneven resource conditions.

This paper seeks to address these intertwined challenges by posing a central question. That is, how can last-mile dairy distribution be optimized in the presence of persistent energy instability while meaningfully integrating both formal and informal delivery networks? Answering this question requires going beyond purely technological fixes or narrow cost-minimization models. It calls for a framework that considers energy volatility as an endogenous variable, and also factors product perishability into decision rules. The framework would also consider network duality as a strategic design consideration rather than an operational inconvenience. Accordingly, the study develops a theoretical hybrid optimization framework that integrates energy reliability parameters, thermal decay dynamics, and cross-network coordination mechanisms within a unified analytical architecture. The objective is not just to minimize spoilage or reduce cost in isolation. It is to reconceptualize last-mile dairy logistics as a system influenced by infrastructural fragility, market heterogeneity, and adaptive behavior. By grounding optimization in these contextual realities, The paper proposes a more nuanced and context-sensitive perspective on cold-chain design in urban Nigeria and similar infrastructure-constrained environments.

2. CONCEPTUAL FOUNDATIONS

2.1 Cold-Chain Fragility Under Energy Instability Cold chains are designed to maintain perishable goods within tight temperature bands to slow microbial growth and extend product life. This is particularly true for dairy products whose safety and quality degrade rapidly when temperature thresholds are breached. In established cold chains, compliance with temperature protocols is largely a matter of well-maintained equipment and disciplined procedures. However, in energy-unstable environments such as many Nigerian cities, power supply is irregular and unpredictable. Frequent grid instability disrupts pre-cooling periods in storage. It forces reliance on backup power generators, which is also characterized with erratic fuel supplies. These consequently make en-route refrigeration performance uncertain and stochastic rather than deterministic. In these situations, temperature exposure becomes a probabilistic event rather than a controlled parameter. Therefore, spoilage risk behaves nonlinearly: short power failure may have minor effects, but longer or unpredictable outages may accelerate spoilage disproportionately and also erode shelf life faster than standard models assume. Moreover, interruptions to power supply change fundamental operational decision: they reduce viable storage duration at hubs, shift route sequencing priorities to account for outage forecasts, complicate decisions about where and when to allocate limited inventory buffers, and force strategic decisions about deploying backup power sources such as generators or solar systems. In practice, this means that energy reliability cannot be treated as a binary condition (available or unavailable) instead, it should be integrated as a probabilistic operational variable that influences storage, routing, and inventory decisions in optimization models under uncertainty. This reconceptualization parallels arguments in Supply chain resilience literature that disruptions should be integrated into optimization logic rather than being considered as external shocks to be addressed post-hoc.

2.2 Formal and Informal Distribution Networks

Traditional supply chain models assume linear flows through structured, capital-intensive networks. This is where formal logistics operators coordinate distribution from centralized warehouses to retail outlets. These actors typically invest in compliant refrigerated fleets, tracking technologies, and standardized handling procedures because they operate under regulatory expectations and service level agreements. In contrast, many African and Asian urban environments host vibrant informal distribution networks. They consisted of market traders, small kiosk owners, and micro-retailers who are deeply embedded in local neighborhoods. These actors often lack formal refrigeration but compensate with flexibility and relational trust with customers. Despite being discarded as inefficient in formal logistics literature, informal actors deliver substantial value through high market penetration. This is common

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in a densely populated urban areas where formal fleets cannot efficiently service micro-clusters of demand. Informal distributors also enable rapid micro-distribution by using motorcycles or human-powered transport, significantly reducing last-mile time and often securing higher customer trust because of social proximity and individualized service. Moreover, because their cost structures are low and adaptive, they can sustain distribution into areas where formal actors find little profitability. The coordination of both formal and informal networks, however, is challenging: formal actors rely on technology and standardized visibility systems that informal traders may not be able to support, while informal actors may lack the capacity to implement expensive sensor systems or complex routing tools. The research challenge is not whether to include informal actors in optimization models, but how to coordinate them in such a way that do not impose unrealistic technological or financial burdens while still harnessing their distribution capabilities. This integrative perspective goes along with emerging research on localized and hybrid supply networks that highlight performance benefits from balancing structure with flexibility.

2.3 Theoretical Anchors

Three complementary theoretical streams ground the hybrid framework proposed in this study. First, Supply Chain Resilience Theory emphasizes the ability of supply networks to absorb disruptions, reconfigure resources, and restore operations without significant performance loss. In the context of energy instability, resilience implies incorporating adaptive capacities that anticipate grid unreliability, manage stock redundancies, and leverage alternative resources to sustain cold chain performance under uncertainty. Second, Resource Orchestration Theory extends resource-based thinking by explaining how heterogeneous resources, formal fleet assets, informal delivery capacity, backup power technologies, and relational market knowledge can be structured, combined, and deployed to create competitive advantage. Specifically, resource orchestration underscores not only what resources are available, but how they are organized and synchronized under dynamic conditions to produce performance outcomes, such as minimizing spoilage or maintaining service levels. Finally, Perishable Inventory and Routing Theory introduces time–temperature decay functions into the decision space, enabling delivery sequencing decisions to reflect real-time degradation risk in perishable products. By integrating these theoretical strands, the hybrid logic treats energy instability not as an intermittent disturbance, but as a fundamental constraint shaping storage, routing, and coordination decisions within an optimized last-mile cold-chain design. Together, they support a holistic optimization framework that is both adaptive and inclusive of diverse network elements.

3. The Hybrid Cold-Chain Optimization Framework

Layer 1: Energy-Adaptive Cold-Chain Configuration

The first layer of the hybrid framework focuses on structural design decisions. It proactively embeds energy reliability as a spatially explicit planning variable. Rather than designing cold chain infrastructure around average demand, this layer prioritizes resource deployment based on energy reliability indices across urban zones. It incorporates the frequency of power failure, duration patterns, and historical grid performance. In areas with frequent power failure, this layer directs placement of micro cold hubs, equipped with robust thermal buffers and diversified power sources to maintain safe storage thresholds. It also allocates solar-powered backup units and hybrid generator systems to maintain continuous temperature control during outages. This reduces over-reliance on fossil fuels and lowering long-term operational costs. Generator capacity distribution decisions balance cost and risk by ensuring that high-volatility zones have greater redundancy, while more stable areas use lower-cost backup options. Informal distributors, who may not have access to advanced refrigeration, can also be supported through ice-based fallback systems and shared cold storage micro-hubs. The mechanism tends to create localized thermal buffers that bridge power gaps. This spatially informed configuration treats energy reliability as a design decision rather than a constraint, enabling more resilient cold-chain infrastructure that aligns with both formal and informal distribution needs.

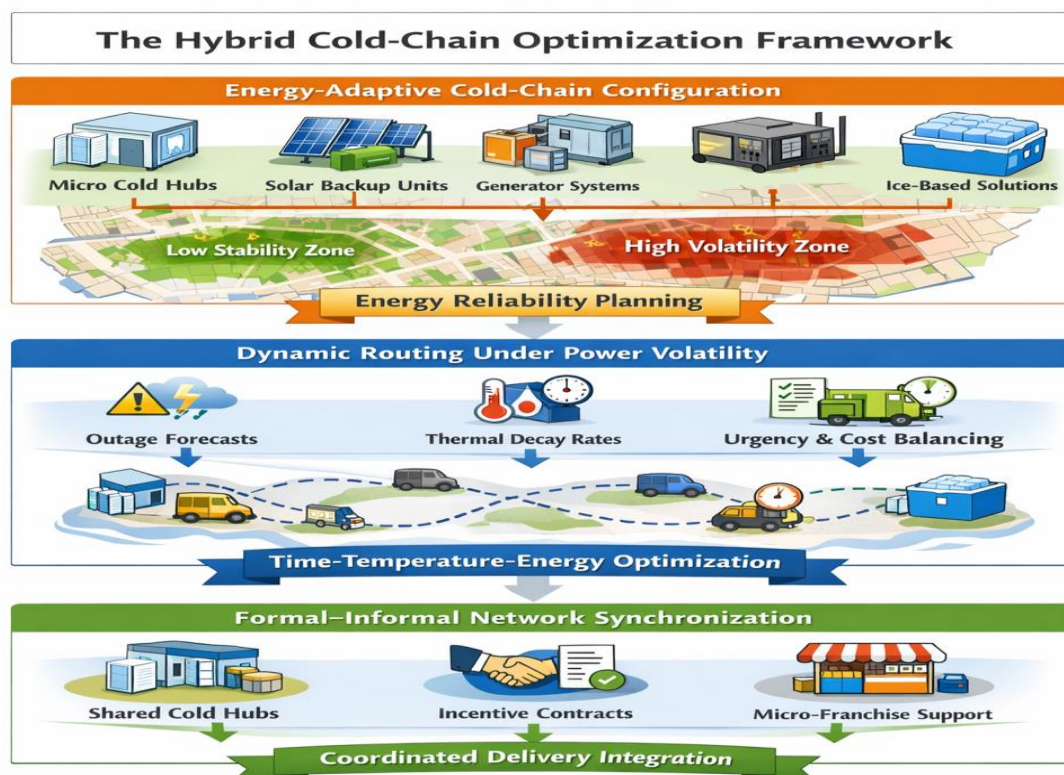
Layer 2: Dynamic Routing Under Power Volatility

The second layer reconceptualizes cold chain routing decisions by integrating energy volatility directly into optimization models. Traditional vehicle routing problems (VRPs) focus on minimizing distance or cost, assuming ambient operating conditions. In contrast, under unstable power conditions, routing must balance real-time or predicted outage windows, product deterioration rates, and delivery urgency based on shelf-life stages. For example, if a neighborhood hub experiences an imminent grid outage, the routing model may prioritize that cluster of deliveries ahead of others to minimize exposure risk. This requires integrating estimated outage forecasts, thermal decay functions, and backup fuel cost thresholds into time-temperature-energy constrained optimization problems. By doing so, routing becomes sensitive not only to spatial and temporal constraints but also to fluctuations in ambient energy conditions that materially affect perishable quality. Such integrated routing models thus shift the optimization objective from distance minimization to multi-objective trade-offs that include spoilage risk, energy cost, and service level outcomes under uncertainty.

Layer 3: Formal–Informal Network Synchronization

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The third layer bridges formal and informal distributors through coordinated integration mechanisms that respect technological and financial limitations. Instead of imposing expensive IoT sensor suites on informal traders, the framework proposes scalable compliance tiers where basic thermal indicators and manual monitoring suffice at lower-technology levels. In this case, more advanced tracking systems are used by formal networks. Integration may involve **micro-franchised cold boxes** supplied by formal firms to informal retailers, **temperature-guarantee incentive contracts** that reward compliance with quality standards, and **shared cold micro-hubs** that enable both network segments to leverage localized storage with minimal duplication. Coordination tools, such as simplified digital dashboards or manual coordination protocols, help ensure that information flows between actors without mandating full IoT implementation. This integrative approach preserves the inclusivity that informal traders bring while improving system wide cold chain performance, enabling last-mile optimization that harnesses the strengths of both formal and informal networks.



The above is a diagrammatic representation of the Hybrid Cold-Chain Optimization Framework describing how energy, inventory, routing, and network integration interact:

4. Trade-Off Analysis: Spoilage versus Customer Satisfaction

It is often assumed, almost intuitively, that reducing spoilage will automatically increase customer satisfaction. In highly controlled supply chains, that assumption may hold: better temperature control preserves product quality, and better quality enhances consumer trust. However, in energy-unstable urban markets, the relationship is far more complex. Spoilage reduction requires investments in backup power systems, redundant refrigeration capacity, and dynamic routing capabilities. These investments increase operational expenditure. In contexts such as urban Nigeria, where dairy consumption is highly price sensitive, rising operating costs can translate into higher retail prices, which may erode customer satisfaction even if product quality improves.

Recent supply chain management research emphasizes that cost-service trade-offs are especially pronounced in perishable supply chains operating under disruption risks. Studies published between 2023 and 2025 in journals such as the *International Journal of Production Economics*, *Journal of Business Logistics*, and *Supply Chain Management: An International Journal* show that resilience investments often improve reliability but may impose short-term cost burdens that affect price competitiveness. The implication is clear: spoilage reduction cannot be pursued in isolation from affordability considerations.

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In the specific context of dairy distribution under energy instability, optimization must simultaneously consider four interacting cost–service dimensions.

First, temperature deviation **cost** represents the financial impact of product degradation when storage or transport temperatures exceed recommended thresholds. This includes direct spoilage losses, reputational damage, and potential regulatory penalties. Empirical studies in cold chain analytics (2023–2024) demonstrate that even brief temperature excursions can significantly reduce remaining shelf life thereby increasing return rates and reducing consumer trust.

Second, fuel or solar investment cost reflects the capital and operational expenditures associated with backup energy systems. Diesel generators incur fuel and maintenance expenses, which are vulnerable to market volatility. Solar systems require higher upfront capital but offer lower long-term operating costs. Contemporary SCM research on sustainable logistics (e.g., 2023–2025 publications in the *Journal of Cleaner Production*) highlights that renewable energy adoption improves environmental performance but requires careful financial modeling to avoid undermining cost competitiveness.

Third, retail price sensitivity must be explicitly incorporated into the optimization logic. In low- and middle-income urban markets, dairy demand elasticity is significant. If enhanced cold chain protection increases retail prices beyond consumers' tolerance thresholds, demand may decline, negating the benefits of reduced spoilage. Research on last-mile affordability in emerging markets (2024, *Transportation Research Part E*) underscores that price stability is a critical determinant of customer satisfaction in fragmented retail environments.

Fourth, service speed expectations influence perceived satisfaction independently of price and quality. Urban consumers increasingly expect reliable and timely product availability. Delays caused by rerouting to manage outage risks may protect quality but harm service perception. Contemporary studies in omni-channel logistics and perishable distribution (2023–2025) show that responsiveness and reliability often weigh as heavily as price in shaping customer loyalty.

Taken together, these dimensions suggest that customer satisfaction in last-mile dairy supply chains is multidimensional, encompassing product quality, product availability, affordability, and timeliness. Accordingly, the proposed framework adopts a joint objective optimization logic. Rather than minimizing spoilage alone, it seeks to minimize the combined function of total spoilage cost and energy backup cost, subject to minimum service-level constraints and price-stability thresholds. In practical terms, this means that investments in backup energy or dynamic routing must be calibrated against acceptable retail price ranges and delivery time standards. The optimization challenge therefore becomes multi-objective and constrained, reflecting the lived realities of urban dairy consumers rather than idealized cost-minimization models.

5. THEORETICAL CONTRIBUTIONS

This study advances supply chain theory in three significant ways.

1. Energy as a Core Optimization Variable

Traditional supply chain models treat electricity reliability as an environmental assumption — rarely interrogated and seldom modeled explicitly. Even resilience frameworks often conceptualize disruptions as episodic shocks rather than chronic infrastructural conditions. By embedding energy reliability directly into routing, inventory, and infrastructure design decisions, this framework reframes energy instability as an endogenous decision variable. Recent resilience research (2023–2025) emphasizes that structural vulnerabilities must be integrated into design logic rather than addressed reactively. In doing so, this study extends resilience theory by operationalizing energy volatility as a probabilistic parameter within cold chain optimization.

2. Reframing Informality

Mainstream SCM literature has historically privileged formal, technology-intensive distribution systems. Informal actors are frequently portrayed as inefficient or transitional. Yet empirical research in emerging economy supply chains (2023–2024) increasingly recognizes the adaptive capacity and embeddedness of informal networks. This study conceptualizes informal distributors not as peripheral actors but as strategic assets whose flexibility enhances resilience during infrastructural disruptions. When formal systems face power outages or congestion bottlenecks, informal distributors often sustain micro-level product availability. By integrating informal actors into optimization design, the framework expands resource orchestration theory to include socially embedded and low-capital assets as legitimate contributors to competitive advantage.

3. Hybrid Resilience Architecture

Most resilience models focus either on infrastructure redundancy or on dynamic operational flexibility. This study proposes a hybrid architecture that combines infrastructure adaptation (micro cold hubs and backup energy systems), algorithmic routing adjustments (time–temperature–energy constrained optimization), and relational coordination mechanisms (formal–informal synchronization). By linking physical, digital, and relational layers into a unified system, the framework contributes to emerging scholarship on hybrid and adaptive supply networks in infrastructure-constrained economies. It shifts the conversation from isolated resilience tools to integrated system design.

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6. Managerial Implications

For dairy producers and logistics firms operating in Nigeria, the implications are practical and strategic.

First, investments in solar-powered micro cold hubs may yield greater spoilage reduction than simply expanding refrigerated fleets. Fleet expansion addresses transport capacity but does not resolve storage vulnerability at neighborhood nodes. Empirical logistics studies (2023–2025) show that localized storage resilience often produces higher marginal returns than transport redundancy in disruption-prone environments.

Second, coordinating informal distributors through shared infrastructure or incentive contracts can reduce last-mile cost without compromising quality. Rather than bypassing informal retailers, firms can equip them with standardized cold boxes or access to shared micro-hubs. This strategy leverages their proximity to consumers while improving quality assurance.

Third, energy risk mapping should precede route optimization exercises. Firms that design routes solely based on distance and traffic patterns may overlook outage hotspots that compromise cold integrity. Integrating energy reliability data into logistics analytics enables more informed infrastructure and routing decisions.

For policymakers, the implications extend beyond firm performance to urban food security. Energy instability directly affects access to safe dairy products. Therefore, urban food policy must incorporate energy reliability as a supply chain variable, not merely a utility issue. Incentives for decentralized renewable cold storage, including tax credits or micro-finance schemes, could stabilize dairy supply and reduce post-harvest losses. Supporting hybrid distribution models that formally recognize informal actors can also strengthen urban food resilience.

7. CONCLUSION

Optimizing last-mile dairy distribution in urban Nigeria requires abandoning assumptions derived from infrastructure-stable contexts. Energy instability is not background noise it is structural and persistent. Informal distribution networks are not marginal anomalies; they are foundational components of the urban food ecosystem.

The hybrid framework developed in this study integrates these realities into a coherent theoretical architecture. By embedding energy reliability into infrastructure configuration, routing algorithms, and cross-network coordination mechanisms, it offers a pathway toward resilient and inclusive dairy distribution systems capable of balancing quality, affordability, and responsiveness.

Future research should move beyond conceptual modeling to empirical validation. Simulation modeling, mixed-integer programming under stochastic outage scenarios, and field data collection across multiple Nigerian cities would allow researchers to test the performance of the framework under varying outage intensities and demand volatility conditions. Comparative studies between cities with different energy reliability indices could further refine optimization parameters.

Ultimately, optimizing cold chains in unstable environments demands more than advanced sensors or sophisticated algorithms. It requires redesigning the underlying logic of coordination — integrating infrastructure, technology, and social networks into a system that reflects the lived realities of urban markets.

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