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Optimizing Lean Cold Chain Performance: A Simulation-Based Study of Almarai's Integrated Food Supply Chain

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Abstract

This paper evaluates whether integrated lean implementation across supply chain drivers can improve cold-chain supply network effectiveness more than partial lean improvements. The study uses Almarai Company as a public-source-informed case context because its public reporting describes a large food and dairy cold-chain network with plants, depots, vehicles, outlets, suppliers, and sustainability priorities. The study does not claim access to internal Almarai operating data. Instead, public sources define the case boundary, and a normalized Monte Carlo simulation compares three scenarios: a baseline proxy, a partial lean improvement scenario, and an integrated lean improvement scenario. The model links lean practices to six supply chain drivers: facilities, inventory, transportation, information, sourcing, and pricing. Performance is evaluated through total cost, lead time, service level, stockout rate, waste rate, inventory turnover, and responsiveness. The simulated results show that integrated lean improvement produces stronger network-level benefits than partial lean improvement. A sensitivity analysis further tests demand and lead-time changes to examine whether the integrated scenario remains robust under operating stress. The contribution is a driver-based simulation framework that converts a general lean supply chain idea into a measurable conference paper for temperature-sensitive food supply networks.

Keywords
Integrated lean, Cold chain, Supply chain drivers, Public-source simulation, Almarai.

1. Introduction

Lean methodology is widely known for reducing waste, improving flow, and strengthening process discipline. However, a general claim that lean improves supply chain performance is no longer sufficient as a research contribution. The more relevant question is whether lean produces stronger benefits when implemented as an integrated operating system across multiple supply chain drivers rather than as an isolated inventory or waste-reduction activity.

Cold-chain food networks provide a suitable setting for this question because product freshness, delivery frequency, temperature control, stock availability, and service reliability are tightly connected. In such networks, improving inventory alone may not improve total performance if transportation, information sharing, depot flow, sourcing reliability, and cost-to-serve decisions remain misaligned.

The original research idea behind this paper focuses on six supply chain drivers: facilities, inventory, transportation, information, sourcing, and pricing. These drivers jointly determine cost, responsiveness, product availability, and service reliability. This conference paper strengthens that idea by examining whether integrated lean improvement across these six drivers outperforms partial lean improvement in a cold-chain supply network.

Almarai Company is selected as an open-source case context because its public annual reporting describes a large food and dairy cold-chain and distribution network. The case is used only to define a realistic operating boundary. The study is not based on internal Almarai data; it is a normalized analytical simulation informed by public disclosures and lean supply chain literature.

The central research question is: To what extent does integrated lean implementation across supply chain drivers improve cold-chain supply network effectiveness compared with partial lean implementation?

1.1 Objectives

To develop a driver-based framework linking lean practices to facilities, inventory, transportation, information, sourcing, and pricing.
To use public sources to define a realistic cold-chain case boundary without claiming access to internal company data.
To compare three scenarios: a baseline proxy, a partial lean improvement scenario, and an integrated lean improvement scenario.
To evaluate the scenarios using cost, lead time, service level, stockout rate, waste rate, inventory turnover, and responsiveness.
To demonstrate whether integrated lean improvement outperforms partial lean improvement in a temperature-sensitive food supply network.

1.2 Research Contribution

The value of this study is not in proving that lean is useful. That point is already established in the literature. The contribution is to show how lean can be evaluated as an integrated driver-based system in a cold-chain context. The study contributes theoretically by linking lean to six supply chain drivers, methodologically by using a public-source-informed simulation approach, and managerially by showing why partial lean improvements may be weaker than integrated network-level alignment.

2. Literature Review

Lean thinking emphasizes waste elimination, flow improvement, customer value, continuous improvement, and standard work (Womack and Jones 1996; Hines et al. 2004; Holweg 2007). In supply chain environments, lean extends beyond internal production and affects supplier coordination, replenishment, transportation planning, information visibility, and order fulfillment (Naylor et al. 1999; Mason-Jones et al. 2000). Shah and Ward (2003; 2007), Bhamu and Sangwan (2014), and Berger et al. (2018) show that lean practice bundles and lean supply chain practices are stronger when implemented as an integrated system rather than isolated tools.

Supply chain performance measurement requires multiple indicators. Beamon (1999) argues that cost alone is insufficient because supply chains must also be assessed through responsiveness, delivery performance, and resource utilization. Gunasekaran et al. (2001; 2004) further emphasize metrics related to delivery reliability, inventory, flexibility, and customer service. For cold-chain networks, these measures become more critical because delays, temperature exposure, and poor flow can increase waste and reduce product quality (Akkerman et al. 2010; Aung and Chang 2014; He et al. 2018).

Research on supply chain strategy distinguishes between lean, agile, and leagile approaches. Lean is effective in reducing waste and cost when processes are stable, while agility is needed when demand and supply conditions are more volatile (Christopher 2000; Naylor et al. 1999). In cold-chain food supply networks, lean should therefore not be interpreted only as inventory reduction. It should also support reliable flow, temperature-controlled distribution, cross-functional coordination, supplier discipline, and service-level stability (Awad et al. 2021; Davoudi et al. 2024; Zhang and Mohammad 2024).

Simulation is appropriate for this gap because it can test complex supply chain behavior under uncertainty without claiming access to confidential operational records (Banks et al. 2010; Law 2015). The gap addressed in this paper is the limited use of driver-based simulation to compare partial and integrated lean implementation in cold-chain supply networks. Many discussions describe lean benefits in general terms, while fewer studies show how integrated lean alignment across facilities, inventory, transportation, information, sourcing, and pricing can be evaluated when only public company information is available. This study addresses the gap using a public-source-informed simulation case and a sensitivity analysis of demand and lead-time changes.

3. Methods

The study uses a public-source-informed Monte Carlo simulation method. Public sources are used only to define the case boundary and operating context of a large cold-chain food network. The simulation values are normalized assumptions derived from lean supply chain logic and are not company operating records. Monte Carlo simulation is used because demand, supply reliability, lead time, waste, and service performance vary probabilistically in supply networks. The method is designed for conference-level analysis where the aim is to compare improvement logic rather than audit actual company performance.

The simulation compares three scenarios. S1 is a baseline proxy representing a complex cold-chain network without explicit lean driver alignment. S2 is a partial lean improvement scenario representing isolated waste and inventory-control improvements. S3 is an integrated lean improvement scenario representing coordinated changes across facilities, inventory, transportation, information, sourcing, and pricing. Figure 1 summarizes the workflow (Table 1).

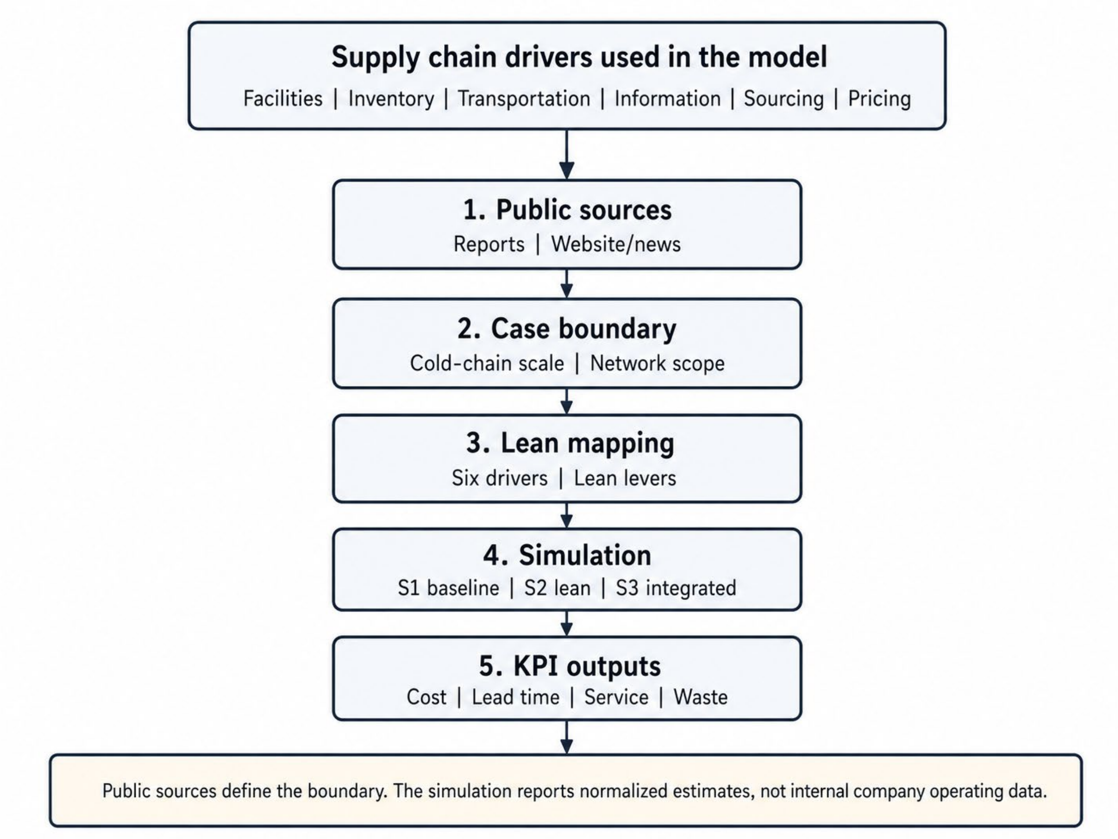

Figure 1. Public-source-informed workflow for evaluating partial and integrated lean improvements

Table 1. Lean interpretation of supply chain drivers in the case model

Driver	Cold-chain interpretation	Lean improvement mechanism
Facilities	Plants, depots, cold stores, distribution points	Flow layout, standard work, reduced waiting
Inventory	Fresh product buffers and replenishment levels	Controlled safety stock, reduced excess, JIT replenishment
Transportation	Vehicle routing, shipment frequency, cold-chain delivery	Route stability, consolidation, reduced emergency movement
Information	Demand signals, replenishment visibility, KPI tracking	Forecast discipline, shorter decision delay, daily management
Sourcing	Supplier reliability and input availability	Supplier performance metrics and delivery agreements
Pricing	Service-cost trade-offs and channel economics	Alignment between delivery service levels and cost-to-serve

4. Data Collection

Data collection was limited to open sources. Almarai public reporting was used to define the scale and relevance of the cold-chain case, while Reuters reporting was used to support the managerial relevance of supply chain investment and capability development. The numerical simulation parameters were not copied from Almarai internal systems. They were normalized to represent relative improvement effects between the three scenarios.

Table 2. Open-source case facts used to define the simulation boundary

Open-source item	Reported information	Use in this study
Manufacturing scale	34 production facilities across 19 plants; annual sales volume above 3.0 billion kg	Justifies a high-volume food manufacturing case boundary
Cold-chain distribution scale	129 sales depots; 12,000+ vehicles; 2.3+ billion kg handled and delivered annually; coverage across 7 countries and 220,000 outlets	Supports a multi-node cold-chain distribution setting
Supplier complexity	1,900+ suppliers and 66,000+ raw material items	Supports sourcing and supplier-reliability assumptions
Quality and certification	FSSC 22000 and ISO 9001 certification across all sites; high-risk ingredient supplier certification target	Supports standardized processes and supplier quality controls
Sustainability targets	Targets include logistics fuel efficiency, energy reduction, waste reduction, water efficiency, and CFC-free depot cold stores	Supports lean waste, energy, transport, and cold-chain improvement logic
Investment direction	Five-year investment plan includes supply chain, sales capabilities, technology, and food security priorities	Supports the managerial relevance of supply-chain improvement

The open-source items in Table 2 are used only to justify the case context. The simulation remains hypothetical and normalized. This distinction is necessary to maintain academic integrity and avoid implying that the results represent audited Almarai operational performance.

Table 3. Simulation assumptions and normalized scenario parameters

Assumption	S1 baseline proxy	S2 partial lean	S3 integrated lean	Rationale
Monte Carlo iterations	1,200	1,200	1,200	Stabilizes average KPI estimates for scenario comparison
Demand distribution	Normal mean 10,000; SD 1,400; minimum 1,500	Same demand stream	Same demand stream	Common demand input isolates improvement effect
Forecast error	17.0%	13.5%	10.5%	Lean discipline improves planning and information flow
Safety stock factor	23.0%	16.5%	13.5%	Lean reduces excess while retaining service protection
Supplier reliability	0.890	0.925	0.960	Supplier alignment improves input reliability
Lead-time mean	6.00 days	4.85 days	3.65 days	Flow, route discipline, and coordination reduce delay
Waste-rate mean	7.5%	4.9%	3.0%	Cold-chain stability and process control reduce waste
Transport factor	1.000	0.935	0.865	Route consolidation and fewer emergency

				movements lower transport burden

Table 3 makes the assumptions explicit so that the simulation is transparent and repeatable. The parameters are intentionally normalized and comparative; they should not be interpreted as audited company values.

5. Results and Discussion

5.1 Numerical Results

Table 4 summarizes the average results across 1,200 Monte Carlo iterations. The key comparison is not simply S1 versus S3, but S2 versus S3. S2 shows the value of partial lean improvement, while S3 shows the additional value of integrating lean across the full set of supply chain drivers.

Table 4. Simulation results by scenario

KPI	S1 baseline proxy	S2 partial lean	S3 integrated lean
Total cost ($/cycle)	92,352	88,659	87,826
Lead time (days)	5.99	4.86	3.65
Service level	96.45%	96.76%	98.39%
Stockout rate	3.55%	3.24%	1.61%
Waste rate	7.47%	4.88%	2.99%
Inventory turnover	1.66	1.71	1.69
Responsiveness index	12.53	15.77	21.47

The results indicate that S3 outperforms S2 across the most important cold-chain performance indicators. Partial lean improvement reduces waste and lead time compared with the baseline, but integrated lean improvement produces stronger reductions in lead time, stockout rate, and waste rate while improving service level and responsiveness. This supports the study argument that lean should be managed as a driver-alignment system rather than as a narrow inventory-reduction practice.

5.2 Graphical Results

Figure 2 presents the simulated percentage improvement of S2 and S3 over the baseline proxy. The chart shows that integrated lean improvement produces the largest gains across most KPIs. This result is expected because cold-chain waste is influenced not only by inventory quantity, but also by transportation reliability, facility flow, information quality, supplier coordination, and pricing-related service decisions.

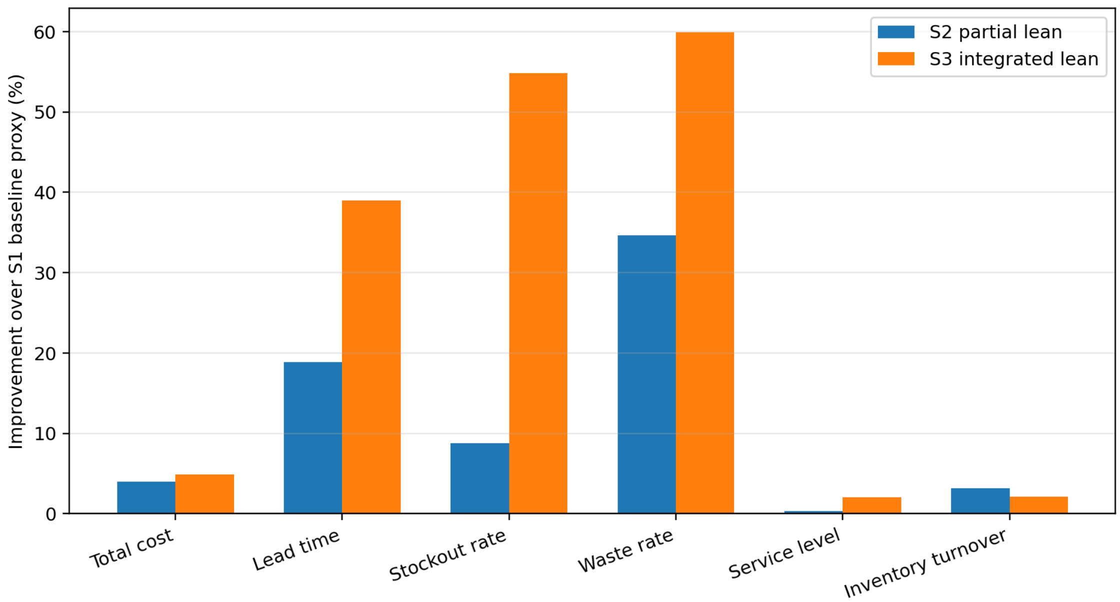

Figure 2. Simulated improvement of partial and integrated lean scenarios over the baseline proxy

5.3 Sensitivity Analysis

A sensitivity analysis was added to test whether the integrated lean scenario remains stronger when the model is exposed to demand and lead-time stress. Four cases were tested: base assumptions, demand increase of 10%, lead-time increase of 20%, and a combined demand and lead-time shock. The analysis focuses on the advantage of S3 over S2 because the research question compares integrated lean with partial lean (Table 5).

Table 5. Sensitivity analysis of demand and lead-time changes

Sensitivity case	Demand multiplier	Lead-time multiplier	S3 cost advantage vs S2	S3 lead-time advantage vs S2	S3 service advantage vs S2	S3 responsiveness advantage vs S2
Base assumptions	1.00	1.00	2.02%	24.28%	1.43 pp	34.68%
Demand +10%	1.10	1.00	2.01%	24.28%	1.47 pp	34.73%
Lead time +20%	1.00	1.20	2.01%	24.28%	1.49 pp	34.73%
Demand +10% and lead time +20%	1.10	1.20	2.00%	24.28%	1.52 pp	34.77%

The sensitivity results show that S3 maintains a positive advantage over S2 under demand growth, lead-time pressure, and combined stress. This does not prove real company performance; it shows that the model logic is robust enough for conference-level scenario analysis and that integrated lean remains preferable to partial lean under the tested assumptions.

5.4 Proposed Improvements

The final improvement logic is to move from isolated lean tools to an integrated lean operating model. First, value stream mapping should cover plant-to-depot-to-outlet flows rather than a single warehouse or production cell. Second, inventory buffers should be linked to delivery frequency, demand visibility, and service-level requirements. Third, transportation planning should focus on route stability, vehicle utilization, delivery window discipline, and fewer emergency movements. Fourth, supplier coordination should be evaluated through reliability, quality, and delivery performance. Fifth, pricing and service policies should reflect the true cost-to-serve of different channels and delivery requirements. Together, these actions convert lean from a local improvement tool into a supply-chain driver alignment mechanism.

5.5 Validation

Welch t-tests were conducted between S2 and S3 across six performance indicators. The purpose is to validate whether the simulated differences between partial lean and integrated lean are statistically distinguishable within the model. These tests validate the simulation behavior, not real company performance (Table 6).

Table 6. Statistical validation of S2 and S3 differences

Metric	Test	t-statistic	p-value	Interpretation
Total Cost	Welch t-test S2 vs. S3	1.27	0.203	Not significant
Lead Time	Welch t-test S2 vs. S3	47.03	<0.001	Significant
Service Level	Welch t-test S2 vs. S3	-7.46	<0.001	Significant
Stockout Rate	Welch t-test S2 vs. S3	7.46	<0.001	Significant
Waste Rate	Welch t-test S2 vs. S3	76.49	<0.001	Significant
Inventory Turnover	Welch t-test S2 vs. S3	1.60	0.111	Not significant

The validation results indicate statistically significant differences between partial lean and integrated lean within the simulated model. For journal-level extension, the model should be calibrated using actual operational data such as route records, depot inventory histories, replenishment cycles, spoilage data, service-level reports, and supplier performance records.

6. Conclusion

This paper refined a general lean supply chain idea into a focused conference study that evaluates integrated lean improvement in a cold-chain supply network. Using Almarai as a public-source-informed case context, the study compared a baseline proxy, a partial lean improvement scenario, and an integrated lean improvement scenario. The results suggest that integrated lean implementation across facilities, inventory, transportation, information, sourcing, and pricing can outperform partial lean improvement by producing stronger network-level gains in cost, lead time, service level, waste rate, stockout rate, inventory turnover, and responsiveness. The added simulation-assumptions table improves transparency, while the sensitivity analysis shows that integrated lean remains stronger under demand and lead-time stress. The main contribution is a measurable driver-based simulation framework for temperature-sensitive supply chains. The limitation is that the model uses normalized simulated data rather than internal company data. Future research can extend this work through empirical calibration, field interviews, route-level analysis, digital twin modeling, and comparison across multiple cold-chain companies.

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