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ORIGINAL ARTICLE

RFID-enabled traceability for perishables: evidence from a system dynamics–Taguchi study

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Abstract

Perishable food supply chains require tight coordination to balance service, cost, and waste. Milk supply chains, in particular, are vulnerable to information delays and handling errors that accelerate expiry and stockouts. This study develops a case-calibrated system dynamics-based simulation of an Irish three-echelon dairy chain to examine whether Radio Frequency Identification (RFID)-enabled traceability actually converts visibility into managerial, operational, and sustainability gains. We compared a periodic-review baseline (N-RFID) and an RFID-enabled scenario (E-RFID) with near-real-time inventory visibility, First-Expired-First-Out (FEFO) rotation, and continuous review, while holding physical lead times constant. A Taguchi L36 design explores—in a structured experimental framework—robustness across lead times, ordering costs, demand and forecast uncertainty, safety-stock policies, and price levels. Outcomes include service performance, demand amplification, average inventories, expiry waste, and net present value. Simulation results show that E-RFID improves retail fill rate from about 95 to 99.9%, cuts expired waste by over 50%, and reduces inventories by up to 30%, while raising supply chain NPV by 5–10%. Benefits are most pronounced under high uncertainty and low-margin conditions, highlighting that RFID complements, rather than replaces, logistics efficiency. We also provide a compact analytical threshold analysis to position economic feasibility and discuss decentralised adoption via cost- and benefit-sharing mechanisms. The modeling framework translates RFID-enabled visibility into measurable operational and economic impacts, identifying robust policy configurations through Taguchi analysis and deriving feasibility thresholds that inform implementation strategies and equitable cost-sharing in decentralised supply chains.

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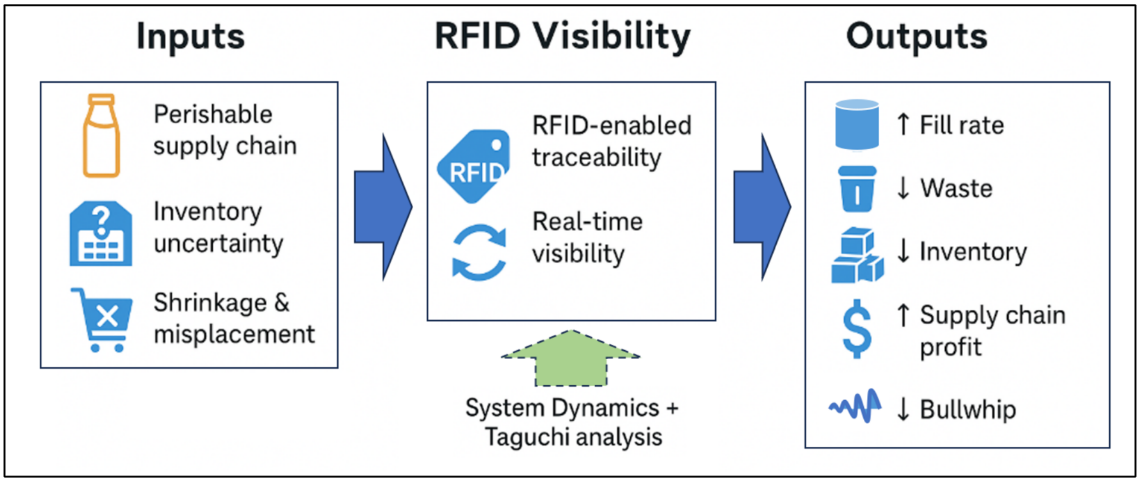
Graphical abstract



Keywords RFID traceability · Perishable supply chains · System dynamics · Taguchi design · FEFO · Inventory visibility · Sustainability · Governance

1 Introduction

A supply chain is a complex network of holons [1] involved in upstream and downstream flows of products, services, finances, and information from a source to a customer, and—under circular models—back to the source for recovery operations [2]. As supply chains grow in operational uncertainty and dynamics complexity [3], performance increasingly depends on coordinated management of inter-organizational flows rather than isolated firm-level optimization [4, 5].

In perishable goods supply chains, coordination becomes especially critical due to limited product shelf life. Time–temperature sensitivity, short replenishment cycles, and stringent service-level targets increase the risk of spoilage and stockouts [6]. These risks are further amplified where cold-chain capacity and visibility are weak, due to strict food safety regulation (e.g., Article 18 of Regulation (EC) N. 178/2002) imposing traceability across production, processing and distribution [7, 8]. Decisions—from design to control to shipping stages—directly affect product deterioration and the marginal cost of time [9]. Temperature excursions, careless handling and partial traceability loss can degrade food quality and can trigger recalls, thus increasing waste and financial losses.

Candan & Toklu [10] report that in 2021, approximately 131 kg of food per EU inhabitant was wasted, equating to €132 billion in economic loss. Enhanced traceability helps mitigate this by enabling real-time stock monitoring, expiry tracking, and proactive First-Expire-First-Out (FEFO) rotation [11], thus reducing waste and improving profitability. Accurate traceability also reduces shrinkage caused by misplaced inventory or poor rotation [12].

Radio Frequency Identification (RFID) technology dominates modern traceability systems due to its ability to automate identification and integrate with other systems [13]. In food supply chains, RFID tags store product data and enable non-line-of-sight mass scanning, enhancing inventory accuracy and monitoring [14]. This improves downstream replenishment, mitigates stockouts, and helps manage losses [15]. Also, Bertolini et al. [16] highlighted that RFID-enabled FIFO reduces shrinkage in perishable food supply chain. Zuo et al. [17] underscore the benefits of RFID's integration with IoT, enabling dynamic shelf-life control and smart packaging for perishable logistics.

At a strategic level, improving perishable supply chains advances sustainability goals. Reducing food waste directly benefits the environment (resource conservation and avoided emissions) while also improving profitability: a classic triple-bottom win (people-planet-profit) as remarked by Parsa et al. [18].

However, the cost of implementing RFID infrastructure and tags in practice raises skepticism, and the benefits (like waste reduction or inventory savings) may be unevenly shared across stakeholders. As noted by Mancusi et al. [19], benefit alignment is foundational for supply chain functioning and longevity. A retailer might capture most spoilage-reduction benefits, while the supplier incurs tagging costs. This misalignment of costs and benefits is common in decentralised supply chains, often leading to under-investment in otherwise worthwhile innovations. Evidence suggests that reducing supply-side uncertainty (e.g., ensuring more stable and predictable returns supply) can align financial and environmental outcomes, whereas demand-side measures alone often do not [20]. These insights are especially relevant in forward perishable supply chains: RFID act as a risk reduction tool by increasing information accuracy, process efficiency and reducing inventory losses [21]. Better supply–demand matching also addresses overproduction and waste. When multiple independent actors are involved, incentive-compatible mechanisms become critical, potentially requiring game-theoretic designs [22]. In decentralised supply chains, with independent stakeholders, collaboration or contract mechanisms are needed so that the investor in RFID is not disadvantaged if downstream actors capture most benefits [23].

This study investigates the impact of RFID-enabled traceability in a decentralized perishable supply chain using a calibrated simulation model of milk distribution [24]. We compare a baseline with manual, periodic review against an RFID-enhanced configuration that introduces accurate inventory data, FEFO enforcement, and continuous review. Physical lead times and governance contracts are held exogenous to isolate technological effects. We evaluate performance via service level, waste, and profitability using a Taguchi L36 design across operational factors such as lead times, order costs, demand variability, and pricing. We address the following research questions (RQs).

RQ1: To what extent does RFID-enabled traceability, coupled with policy retuning, improve service, waste, inventory levels, and bullwhip in a perishable supply chain?

RQ2: How robust are these performance improvements under varying operational conditions?

RQ3: Under which combinations of cost and shrinkage conditions is RFID economically justified for decentralized actors?

We answer RQ1 and RQ2 through a simulation experiment, and address RQ3 using analytical threshold modeling and discussion of governance implications.

This paper contributes to the literature by providing a case-calibrated, simulation–Taguchi assessment of RFID's impact on perishable supply chain performance and robustness. Furthermore, it provides practical implications deriving managerial insights for decentralized settings, highlighting cost–benefit asymmetries and outlining risk-sharing strategies.

The rest of the paper proceeds as follows: Sect. 2 reviews perishables supply chains, RFID adoption, and coordination mechanisms. Section 3 outlines the modeling and experimental setup. Section 4 presents the case study and simulation results. Section 5 discusses results, managerial implications and future research. Section 6 concludes.

2 Background

2.1 Perishables supply chain management

Perishable products – i.e., fresh food, dairy, pharmaceuticals, medicals etc.—are characterized by finite shelf lives and often require controlled storage conditions, making replenishment and issuing decisions time-critical [25]. Traditional inventory models need to be extended to account for product aging and expiration, such as Dobson et al. [26], who proposed expanding the traditional Economic Orders Quantity models (EOQ) to perishable goods. Also, policies like FEFO, FIFO, and shelf-space allocation have been reviewed as levers to balance service and waste [27] [28]. Efficient perishables supply chains aim to ensuring high product availability (service level) while keeping expiration-related losses low [29]. This often requires tighter coordination and information sharing across stages. For instance, as per Ketzenberg et al. [30], when a retailer shares accurate on-hand inventory and upcoming expiry information, the supplier can adjust production and delivery plans accordingly. Recent evidence from European grocery retail [31] shows that efforts to keep "shelves full" often involve planned disposals of expired perishables; insufficient coordination across upstream supply flows in terms of logistics, distribution and store operations. This amplifies both waste and out-of-stocks, revealing a misalignment between supply and demand.

A recent study from Birkmaier et al. [32] finds two primary levers to cut waste in perishables without raising stockouts: (i) short-term, data-driven forecasting tightly integrated with replenishment planning, and (ii) vertical information sharing to align decisions across upstream and downstream supply actors.

Ultimately, the service–waste tension in perishables supply chains strongly concerns short shelf lives, forecasting uncertainty and limited end-to-end visibility. Addressing such issues requires coordination among supply actors, across echelons, enabled by accurate, timely information sharing [33]. Cross-sector evidence from the blood supply chain similarly shows that perishable logistics benefit from simulation-guided policies that cut shortages and outdates while balancing environmental impacts [34]. Building on these insights, we examine RFID-enabled traceability as a key enabler of real-time data sharing, inventory visibility and, in turn, inventory management decisions able to reduce expiry losses while maintaining high service levels.

2.2 Traceability and RFID in food supply chains

Traceability systems in Supply Chain Management (SCM) are designed to capture, store and share product and process-event data (e.g.: identifiers, origin, locations, timestamps, handlers/custodians, relevant condition attributes), so that a product's history and current status can be reconstructed across the supply network [35]. In the food industry, European regulations mandate at least "one step back–one step forward" traceability for safety purposes [36]. Beyond compliance, both internal (within-firm) and external (cross-echelon) traceability contribute to create real-time visibility. RFID is consistently used to enable this visibility and can be integrated with secure data-sharing architectures and, where appropriate, blockchain-based auditability. As shown by Cromwell et al. [37], RFID can be integrated with digital, blockchain-based traceability, contributing to address security and privacy risks that affect firms, consumers and public authorities' processes.

A large body of analytical and empirical work shows that RFID provides comprehensive benefits across diverse dimensions, i.e.: customers relationship management, production planning and production management, material management, enterprise resource planning and financial management [38]. However, the main focus of scholars typically goes on how RFID improved record accuracy, reduces misplacement, and supports replenishment by shrinking information delays, thus, dampening the bullwhip effect and lowering average inventories and safety stocks without degrading service [21].

In perishables, effective FEFO implementation depends on reliable item- or batch-level age information. On this, RFID/IoT systems have the capacity to capture expiry dates and time–temperature histories [17], providing age visibility and enabling dynamic shelf-life control for rotation [39]. Time–temperature history has measurable decision value for distribution and issuing, reinforcing FEFO and prioritization by remaining shelf life.

Despite these benefits, Masekwana et Jokonya [40] remarked that adoption often stalls due to recurring tag and infrastructure costs, systems-integration complexity, and security/privacy concerns, along with limited skills, insufficient managerial support, reliance on external maintenance/services and regulatory constraints. Moreover, successful traceability requires clear data governance such as access rights and GDPR compliance, or master-data quality, all of which condition actual benefits.

As RFID delivers visibility benefits beyond the investing party, technology adoption in decentralised supply networks is contingent on governance, i.e., the allocation of costs and benefits across echelons. We therefore review coordination and risk-sharing mechanisms and position RFID-enabled traceability as a complement that reduces parameter uncertainty and enlarges the scope for coordination contracts.

2.3 Supply chain coordination and risk sharing

Coordination mechanisms in perishables supply chains, as noted, are fundamental to align the decisions so that every stakeholder, across echelons, can share and capture both joint and individual value. Typically, in decentralised supply chains, costs and benefits are shared asymmetrically across echelons, requiring tailored benefit-sharing and coordination analyses. Tao et al. [41] show—using a game-theoretic model with a dominant retailer and two competing suppliers—that strategic incentives can shape RFID uptake as a function of tag costs and inventory availability (resulting in record accuracy), addressing uneven gains between upstream and downstream actors. For perishables specifically, poor record accuracy leads to late-found, expired items—direct waste and unsold costs [15].

A vast body of operations-management research has developed and analysed coordination mechanisms—ranging from simple wholesale-price contracts to buy-back, revenue-sharing, quantity-flexibility, two-part tariffs, and hybrid schemes tailored to perishables. In perishables supply chain subject to demand and yield uncertainty, Chen et al. [42] proposed a joint coordination contract combining revenue-sharing with quantity-discount mechanisms to synchronize decisions, reducing waste and profit variability. Similarly, Pourmohammad-Zia et al. [43] studied a vendor-managed-inventory (VMI) arrangement with a cost-sharing contract that compensates upstream partners for freshness-preserving investments and demand fluctuations, improving overall profit and market coverage. Buy-back contracts address the allocation of demand risk—especially unsold inventory risk—by raising the retailer's effective salvage value, encouraging larger order quantities (higher service levels) while transferring part of the overstock risk upstream [44]. Buy-backs can also discipline upstream opportunism and, in some structures, implement the industry-profit-maximising outcome, with effectiveness shaped by upstream costs and demand elasticity [45].

Similarly, revenue-sharing can stimulate stocking and market expansion by splitting downstream rewards and reducing successive markups in decentralised channels. In closed-loop settings with used-product returns and information asymmetry, revenue-sharing and two-part pricing can coordinate the channel under different power structures and deliver Pareto improvements [46]. In CLSCs with end-of-use/life returns, dynamic revenue/cost-sharing contracts help manage uncertainty in return volumes and quality [47].

In decentralised channels, standard contracts generally fail to implement the first-best allocation, producing over- or under-supply relative to a centralised setting [48]. Such inefficiency can be mitigated by opportunely calibrated coordination schemes, such as revenue-sharing augmented with two-part tariffs [49]. Under environmental regulation, revenue-sharing coordination in CLSC can raise profits and improve environmental outcomes (e.g., higher recovery, lower emissions), as shown under cap-and-trade policy [50].

These insights remark that traceability reduces uncertainty on inventory records and remaining shelf life, which tightens the feasible set of coordinating contract parameters and enlarges the Pareto set. Therefore, considerations on supply coordination and risk sharing can be assumed structural, rather than product-specific, because they concern how incentives are aligned between echelons. Hence, they extend directly to perishable supply chains, where the same mechanisms apply with spoilage- and yield-adjusted parameters.

3 Materials and methods

To assess the impact of RFID-enabled traceability in a perishable supply chain, we use a System Dynamics (SD) logic, well suited to feedback loops, stock accumulations, and information/lead-time delays in operations [51]. SD matches the aggregate scope of this study, capturing continuous product and information flows across echelons, long-run trends in inventory and waste, product ageing, and delay-driven replenishment. Recent work also highlights SD's value for visualizing the propagation of disruptions across supply networks [52]. We simulate at a daily time step ($\Delta t = 1$ day) over multiple years to observe transient and steady-state behavior under varied conditions. The context is an Irish milk supply chain, developed with an Irish higher-education partner and a national grocery distributor–retailer that provided data to calibrate demand patterns, lead times and perishability. While grounded in this case, the proposed model structure is generic and transferable to other perishable products via parameterization. In the case study (Sect. 4), we instantiate this generic structure with a real Irish milk chain: we map real actors to the three echelons, calibrate demand/lead times/perishability from partner data, and then evaluate N-RFID vs E-RFID on service, waste, inventories, and cost. We first show the case context and data, then run the policy scenarios, and finally discuss robustness via the Taguchi design.

3.1 Supply chain modeling

We consider a three-echelon chain for fluid milk: (1) dairy processors (finished product), (2) wholesalers/distribution centers (DCs), and (3) retailers. This mirrors common Irish practice where regional dairies supply retailers directly or via DCs. We model a single product class with multiple production/shipment batches over time. Each echelon has inventory stocks, inflows/outflows, and ordering/production decision rules.

Figure 1 summarizes physical and information flows used to structure the SD model. In detail, forward logistics is marked in green arrows; returns in red, surplus diversion in purple, disposal in black and information/traceability flows are in dashed blue. This map anchors the stock-and-flow formulation.

For our case, the dairy node aggregates the partnered processor's finished-goods buffer; the wholesalers node represents the national distributor's regional depot; and the retailer node represents a typical high-volume store format used in our dataset.

3.1.1 Scenario definitions, information flows and decision rules

We model two scenarios with different information flow assumptions and ordering logic: (i) the baseline scenario, with no adoption of RFID traceability (hereafter N-RFID), and (ii) the RFID-enabled scenario (hereafter E-RFID). Beyond the technical RFID implementation, the key conceptual difference between the two scenarios lies in how inventory information is shared and how orders are triggered.

In N-RFID, each echelon orders on local, delayed, and imperfect information. The retailer reviews weekly and orders the wholesaler who, in turn, reviews biweekly and orders the dairy. Manual records and shrinkage/misplacements are assumed to introduce inaccuracies in the N-RFID. Also, the retailer does not have visibility of dairy inventory, and vice-versa. This sequential, low-visibility structure generates bullwhip effects: small demand shocks amplify upstream via batch ordering and reactive forecasts [53]. We model forecasting error and reaction delays, so stockouts at retail persist until the next review and can trigger over-ordering. Safety stocks are, therefore, maintained at all echelons, raising average inventories and periodically producing over/under-stock.

In E-RFID, real-time retail inventory and sales are tracked and shared instantly with the wholesaler and dairy. A near-continuous review replenishment policy triggers orders automatically when store stock falls below a threshold, thus allowing upstream echelons to replenish just-in-time. Information delay is effectively zero (to be compared to about 1 week in N-RFID), removing manual ordering and related errors. Accordingly, orders become smaller and more frequent, enabling lower average inventories with minimal stockouts. This motivates our assumption of near-100% accuracy of inventory record, so that upstream actors precisely match supply to actual needs. Under these assumptions, in E-RFID, the shared inventory and age information can be considered fully reliable. Lower read rates or inconsistent compliance would reduce the effective visibility advantage and shift system behaviour toward the N-RFID regime. While we do not impose detailed capacity limits, dairy production follows visible consumption with a short adjustment delay, smoothing swings seen in N-RFID. Over longer time horizons, such RFID-enabled visibility is expected to reduce

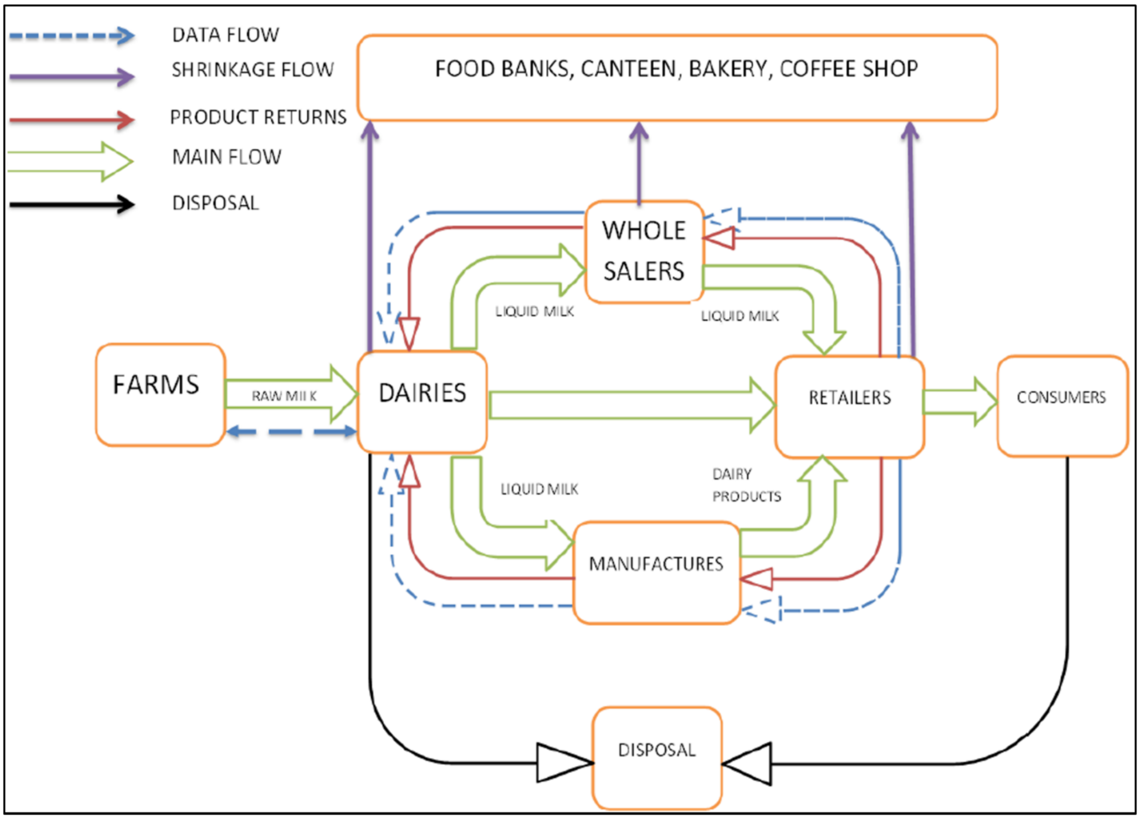


Fig. 1 Irish dairy supply chain and associated flows

over-production and waste, while improving service and total cost.

Such information-flow changes influence decision-making synchronisation across all three echelons. Under N-RFID, retailer, wholesaler, and dairy each act on locally delayed and imperfect signals, thus replenishment decisions are sequential and weakly coordinated. Under E-RFID, shared near-real-time inventory and sales visibility collapses inter-echelon information delays and allows upstream actors to respond directly to downstream consumption. As a result, ordering shifts from forecast-driven periodic adjustments to consumption-driven continuous replenishment. This favors reducing batching and dampening amplification along the chain.

3.1.2 Consumer demand

Retail demand is set as a daily stochastic withdrawal calibrated to case data, *i.e.*, hundreds of units per day with 10–20% variability and mild seasonality. In Ireland's pasture-based system, milk supply is highly seasonal [54], since production follows the grass growth cycle driven by rainfall and temperature, resulting in about 75% of annual deliveries occurring between April and September. Therefore, in the model, upstream capacity varies seasonally with a grass/precipitation signal: when rainfall supports pasture growth, effective production capacity rises; during drier/colder months it falls. This captures the observed Irish pattern and couples climate variability to the milk available to downstream echelons.

3.1.3 Replenishment policy

In N-RFID, retailer and wholesaler use periodic-review base-stock targets—weekly and bi-weekly, respectively—sized to expected demand plus safety stock. In E-RFID, continuous-review in VMI-like ordering exploits accurate, real-time visibility to cut or eliminate safety stocks while sustaining service. Prior literature suggests that such visibility dampens the bullwhip effect and permits lower safety stocks without decreasing service level [21].

3.1.4 Lead times

We incorporated lead times for order fulfillment at each stage. When the retailer sends an order to the DC, a transportation delay is considered. Physical transit or processing times are set consistently for the case: from DC to Retailer about 1 day from dairy to DC 1, 2 or 3 days. These do not change among N-RFID and E-RFID cases. Lead times add pipeline stock and motivate safety stock in N-RFID. Under RFID, the same lead times are countered by faster decision response (frequent ordering), improving responsiveness and limiting both over- and under-stock risks.

3.1.5 Perishability and shrinkage modeling

The core aspect of the model is the inherent perishability of milk and the tracking of inventory age and spoilage. Pasteurized milk has a limited shelf life, set to 9 days as per Al-Farsi et al. [55]. To capture this, we track age and remove expired units as waste, assuming FIFO by default. N-RFID includes avoidable handling losses (mis-rotation or misplacement) as shrinkage, lowering effective shelf-life usage. With RFID, item-level visibility enables reliable FEFO and stock location, so avoidable shrinkage is set to zero and only unavoidable expiry remains. RFID also helps pinpoint loss points and reduce expiry through better process control. The real-time monitoring further reduces pre-sale expiration, as per Zuo et al. [17]. It is noteworthy to note that, while RFID visibility improves inventory accuracy, strict FEFO application enabled by item-level age identification specifically contributes to issuing decisions by prioritizing products with shorter remaining shelf life. This reduces residual aged stock and late-found expiries beyond the effects of improved stock visibility alone.

We did not explicitly model cold-chain related failures—being outside the scope of the current model—but we remark that RFID sensors could also reduce spoilage through temperature control.

Figure 2 provides the Integration DEFinition for Function Modeling (IDEF0) diagram of the end-to-end dairy supply chain. The upstream farm is treated as an exogenous supplier in our SD model: it appears in Fig. 2 to contextualize flows but is not explicitly modeled as a stock. Solid red arrows trace physical product movements from farm to dairy, wholesaler, and retailer (with returns/secondary products), while dashed arrows capture the associated information exchanges, i.e., orders, demand signals, prices, lead times, and traceability messages (e.g., barcodes). The callouts indicate local decision logics and constraints (inventory costs, priority rules, regulations). This map complements the stock-and-flow view by clarifying where decisions and data are generated and how they travel across echelons.

Table 1 (below) reports the core model inputs and scenario assumptions exposed in this section.

3.2 System dynamics model structure and performance metrics

The SD model implements the three-echelon supply chain (dairy, wholesaler, retailer) feedback-based inventory and ordering policy at each level, along with mechanisms for backlog (unfulfilled orders) and perishable inventory (aging and spoilage).

The dairy uses a standard feedback inventory policy calibrated to the case: it targets a desired stock equal to expected demand over the 3-day delivery lead time and adjusts toward that target over a 14-day correction time to avoid overreaction to noise. Expected demand is formed from wholesaler orders passed through a short information delay (reflecting order processing/confirmation). A reorder-point rule adds safety stock proportional to observed demand variability—computed from an exponentially smoothed demand signal—and a tunable service factor k. Production release (i.e., order issuance to the shop floor) occur when the on-hand/position falls below the reorder point. In parallel, an order-pipeline correction loop keeps outstanding orders aligned with the desired pipeline implied by the lead time, preventing both starvation and overfilling of work-in-process. These inventory adjustments and pipeline correction structures constitute the core feedback loops of the SD model. In N-RFID, demand and inventory information entering these loops is delayed and periodically—manually—updated, causing amplified corrections and oscillatory ordering responses. Instead, in E-RFID, shared near-real-time visibility reduces information delay and distortion in the feedback signals, so adjustments are based on actual stock positions and consumption. This structural difference explains the dampening of order variability and backlog propagation observed under RFID.

Service performance is tracked via a backlog stock that rises whenever incoming orders temporarily exceed shipment capacity and then drains as shipments are made. Perishability is represented with an aging chain: inventory advances daily through age cohorts, and units that reach the end of their 9-day shelf life are removed as spoilage. This enforces FEFO rotation and prevents accumulation of over-aged stock. Figure 3 reports the described Dairy echelon.

Building downstream the same logic, with echelon-specific parameters, Fig. 4 shows the wholesaler echelon, which closely mirrors the dairy's presented structure.

The wholesaler maintains an inventory stock, a backlog stock, and a reorder-point–based ordering process governed by inventory- and order-correction loops. Retailer orders feed the backlog if immediate fulfilment is not possible. The wholesaler then places its own orders to the dairy based on forecasted retailer demand and inventory correction. The wholesaler's inventory accumulates shipments from the dairy and depletes through shipments to the retailer. Responsiveness is shaped by the dairy-to-DC lead time and the wholesaler's safety-stock multiplier k, which together determine how aggressively it buffers variability while avoiding excessive holdings.

Figure 5 depicts the retailer echelon, the final stage where consumer demand is met.

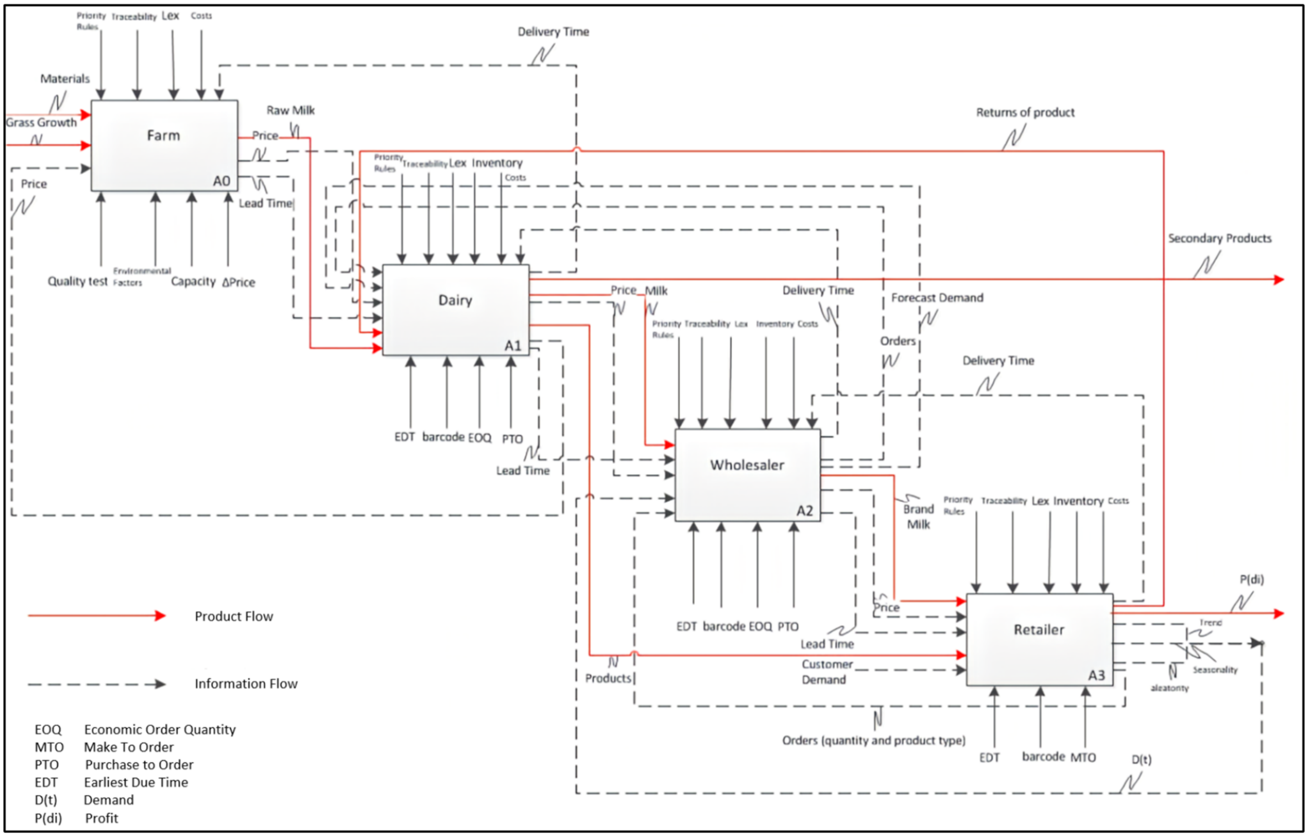


Fig. 2 The analysed end-to-end Irish milk supply chain (IDEF0 map)

Table 1 Inputs and scenario assumptions for the supply chain model

Model element	Parameterization in model	N-RFID	E-RFID	Source
SC structure	3-echelon	Same	Same	Case/industry
Retail demand	Daily stochastic demand with 10–20% variability and seasonality	Same	Same	Case/industry
Seasonal supply	Upstream capacity varies with rainfall cycle	Same	Same	Literature assumption
Review and ordering policy	Replenishment logic	Periodic	Continuous	Scenario assumption
Information visibility	Inventory information sharing across echelons	Local (delayed)	Shared (real-time)	Scenario assumption
Inventory accuracy	Record accuracy	Imperfect	Near-perfect	Scenario assumption
Lead times	DC to Retail = 1 day Dairy to DC = 1–3 days	Same	Same	Case/industry
Perishability and issuing	Shelf life 9 days; FIFO vs FEFO; avoidable shrinkage	FIFO + shrinkage	FEFO + no avoidable shrinkage	Literature assumption

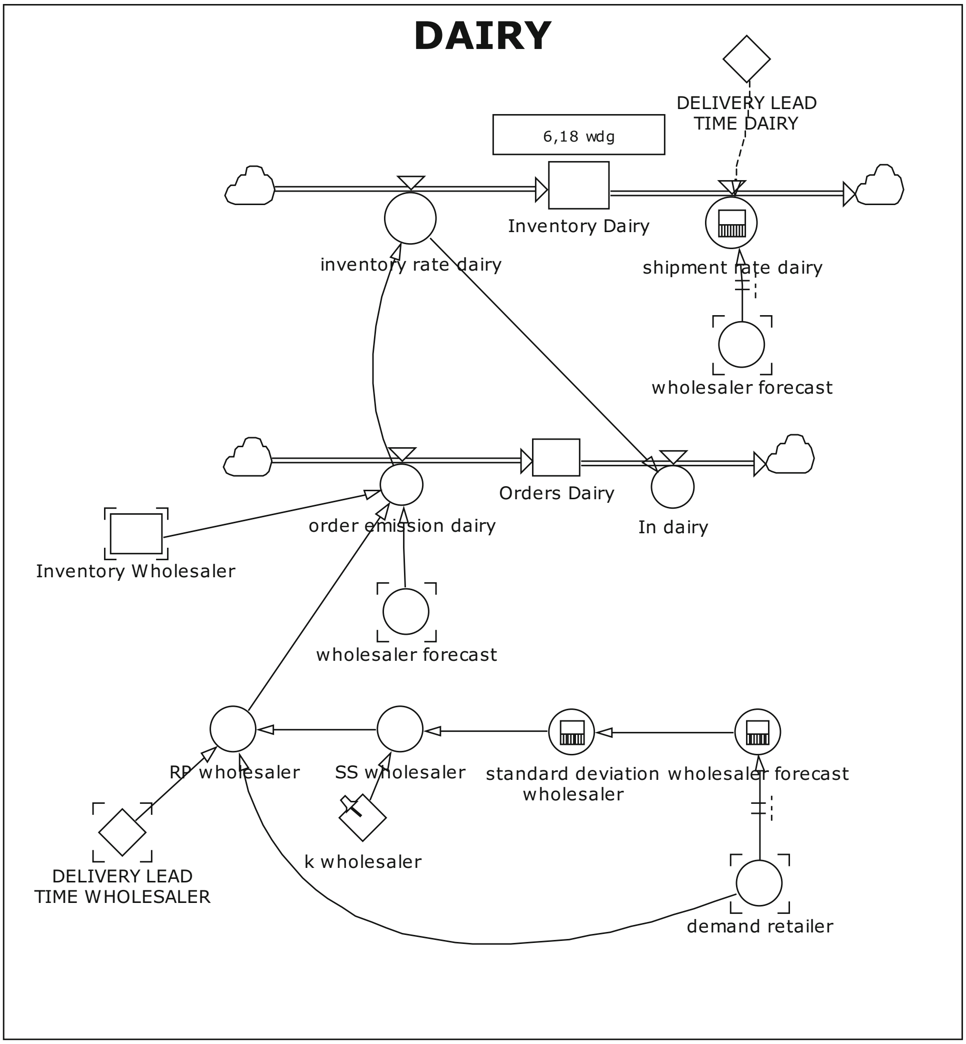


Fig. 3 System dynamics model structure of the Dairy echelon

The retailer's inventory stock increases with receipts from the wholesaler and decreases with sales. When stock falls below the retailer's reorder point, a new order is triggered from a decision block based on forecasted demand and inventory correction, with a safety factor k and the DC-to-store lead time governing target coverage. Unmet demand accumulates in retailer's backlog. A waste accumulator (not shown in the figure for brevity) removes items that expire on the shelf using the same aging-chain mechanism, allowing direct measurement of service level, on-shelf availability, expiry-related waste and, in the E-RFID scenario, the improvements delivered by higher record accuracy and more responsive replenishment.

3.3 Analytical modeling of the impact of RFID-based traceability

Before proceeding to the dynamic simulation, an analytical evaluation was carried out to assess under which conditions the implementation of an RFID-based traceability system is economically justified in a supply chain. The case study will use these results as a lens to interpret the simulated economics under realistic dynamics.

Although the benefits of RFID are well known, both fixed and variable costs associated with its deployment can substantially affect diverse echelons. As noted, costs and benefits may not symmetrically distribute along the supply chain: in most cases, the retailer benefits more than the upstream actors. In this analytical framework, we assume that the three supply-chain members (dairy, wholesaler, retailer) share both fixed and variable RFID costs. The goals of this modeling are: (i) quantify the trade-off between costs and benefits; (ii) determine when RFID increases total profit; (iii) understand how RFID affects order policies, inventory levels, and profitability in both centralized and decentralized supply-chain configurations. Table 2 reports the variables and parameters assumed.

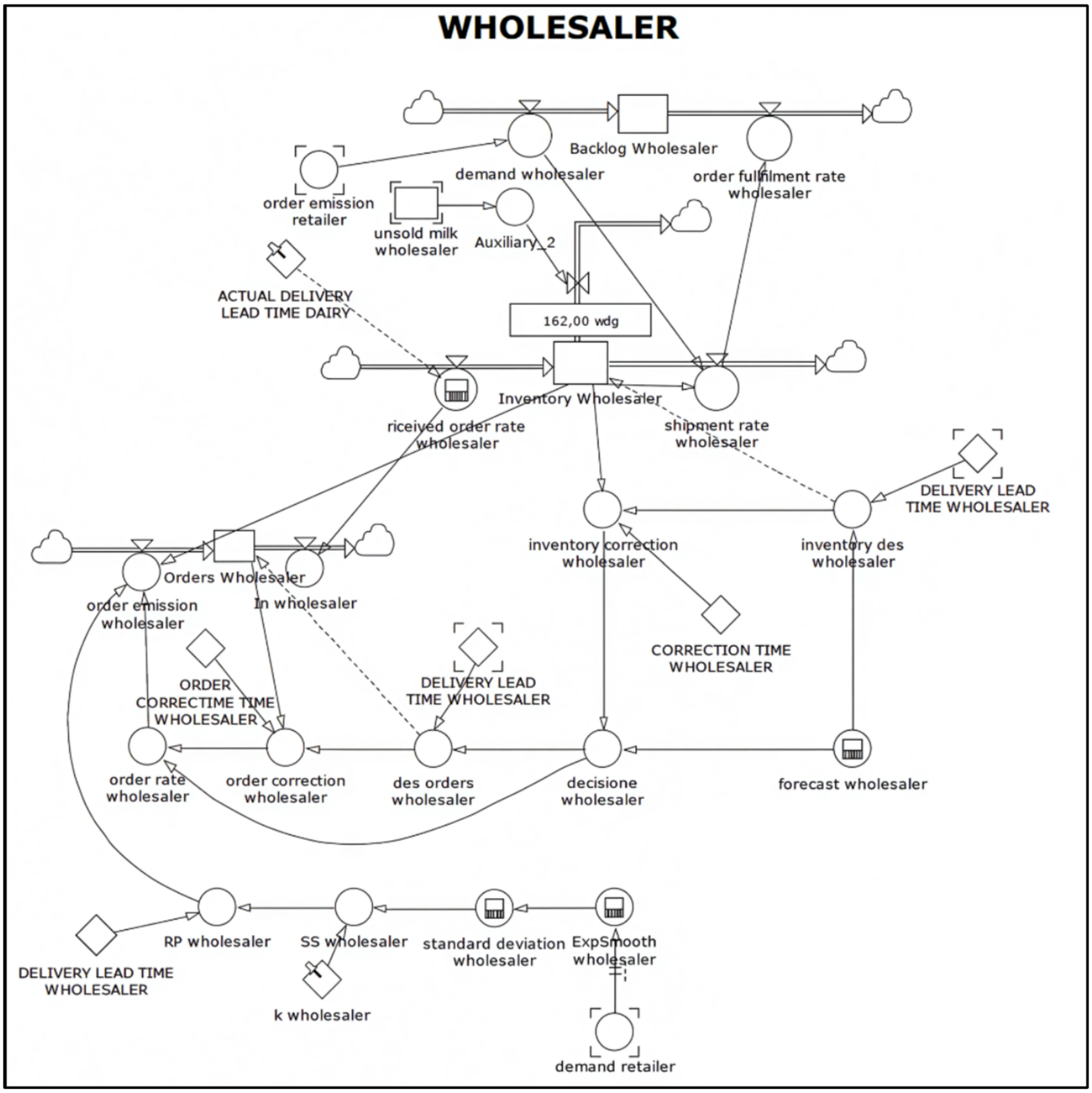


Fig. 4 System dynamics model structure of the Wholesaler echelon (inventory and order management)

Without RFID, part of the product is unavailable due to shrinkage and misplacement. In this formulation, α and β denote availability fractions after shrinkage and misplacement effects respectively. The corresponding loss shares are therefore (1 − α) as shrinkage loss (i.e.: SL) and (1 − β) as the misplacement loss (i.e., ML). Assuming these two loss mechanisms act as separable additive losses (i.e., without double counting the same unit), the effective availability factor is:

$$\lambda_1 = 1 - (SL + ML) = 1 - (1 - \alpha + 1 - \beta) = \alpha + \beta - 1$$

With RFID, misplacement is assumed fully eliminated, meaning that ML becomes zero (1 − β = 0), therefore β = 1. Starting from the N-RFID availability expression λ1, setting β = 1 gives λ2 = α. RFID additionally recovers a fraction δ of the SL, i.e., (1 − α), so the effective availability becomes:

$$\lambda_2 = \alpha + \delta(1 - \alpha)$$

3.3.1 Centralized Supply Chain (CSC)

In the centralised configuration, all supply chain members cooperate to maximise total profit. The two scenarios are analysed N-RFID and E-RFID.

3.4 Case A: CSC, N-RFID scenario

Without RFID, product losses occur due to both shrinkage and misplacement. Assuming these losses are independent,

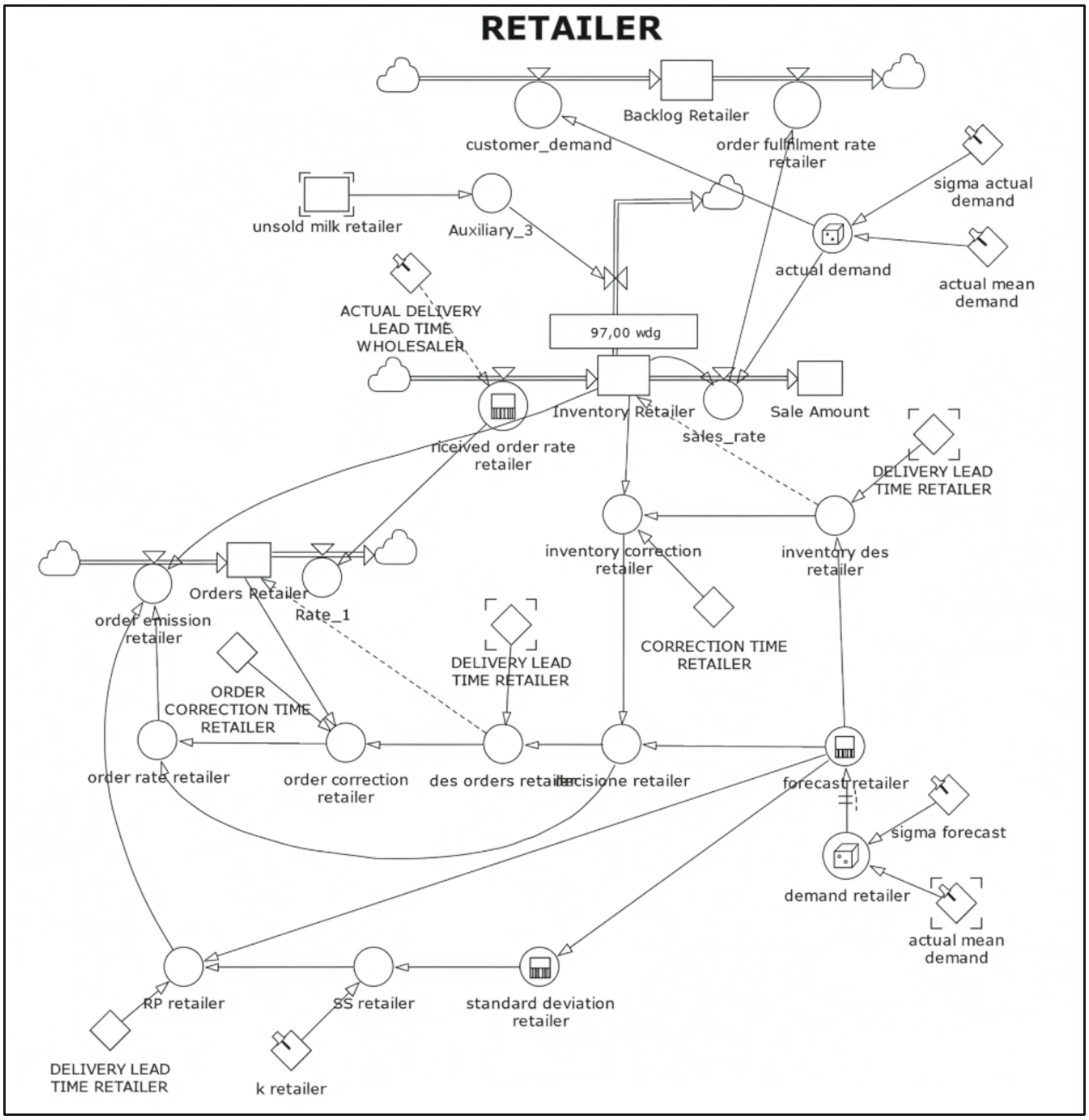


Fig. 5 System dynamics model of the Retailer echelon (inventory, backlog, and ordering processes)

the effective product availability becomes λ_1. The expected profit function is:

$$\begin{aligned}\Pi_{N-RFID,c}(Q) = p\int_0^{\infty} min\,(\lambda_1 Q,\\ x)\,dF(x) + s\int_0^{\lambda_1 Q}(\lambda_1 Q - x)dF(x)\\ - g\int_{\lambda_1 Q}^{\infty}(x - \lambda_1 Q)dF(x)\\ + s\,(1-\beta)\,Q - cQ\end{aligned}$$

The first integral represents expected sales revenue. The second represents the residual value of unsold products. The third represents expected shortage (backlog) costs. The fourth term accounts for the value of misplaced items recovered at inventory time. The term cQ represents total purchasing cost. Maximizing this function yields the optimal order quantity, as follows:

$$Q^*_{N-RFID,c} = \frac{1}{\lambda_1}F^{-1}[1 - \frac{c - s\alpha}{\lambda_1(p + g - s)}]$$

3.5 Case B: CSC, E-RFID scenario

RFID eliminates misplacement and partially recovers shrinkage through better visibility. Thus, availability improves to λ_2. Here, each item has a tagging cost t and there is a fixed

Table 2 Symbols and units

Symbol	Measure	Description
$\Pi(Q)$	€	Expected profit
Q	units	Order quantity
c	€/unit	Unit purchasing cost
g	€/unit	Stockout/backlog cost
p	€/unit	Selling price
s	€/unit	Salvage value (s < c < p)
t	€/unit	RFID tag cost
g_D	€/unit	Dairy stockout cost
g_r	€/unit	Retailer stockout cost
K	€	Fixed cost for RFID system implementation
$B^*(t,K)$	€	Profit difference between E-RFID and N-RFID scenarios
θ_t	–	Fraction of tag cost borne by dairy
θ_K	–	Fraction of fixed cost borne by dairy
x	Units	Random demand with cumulative distribution *F(x)*
α	–	Availability under shrinkage
β	–	Availability under misplacement
δ	–	Shrinkage recovery factor with RFID
λ_1	–	Effective availability (N-RFID)
λ_2	–	Effective availability (E-RFID)

investment cost K. The new expected profit, therefore, is:

$$\Pi_{E-RFID,c}(Q) = p\int_0^\infty min\,(\lambda_2 Q, x)\,dF(x) + s\int_0^{\lambda_2 Q}(\lambda_2 Q - x)dF(x) - g\int_{\lambda_2 Q}^{\infty}(x - \lambda_2 Q)dF(x) - (c+t)\,Q - K$$

The optimal order quantity becomes:

$$Q^*_{E-RFID,c} = \frac{1}{\lambda_2}F^{-1}[\frac{p+g}{p+g+s} - \frac{c+t}{\lambda_2(p+g-s)}]$$

3.6 Feasibility thresholds

To support decision-making, we derive threshold values of the recovery rate δ and tag cost *t* that make RFID adoption economically viable.

To obtain closed-form analytical expressions, the demand is assumed uniformly distributed. Under this assumption, the formulas above directly define the closed-form optimal order quantities $Q^*_{N-RFID,c}$ and $Q^*_{E-RFID,c}$. The analytical model allows derivation of threshold values of the recovery rate δ and tag cost t that make RFID adoption economically viable.

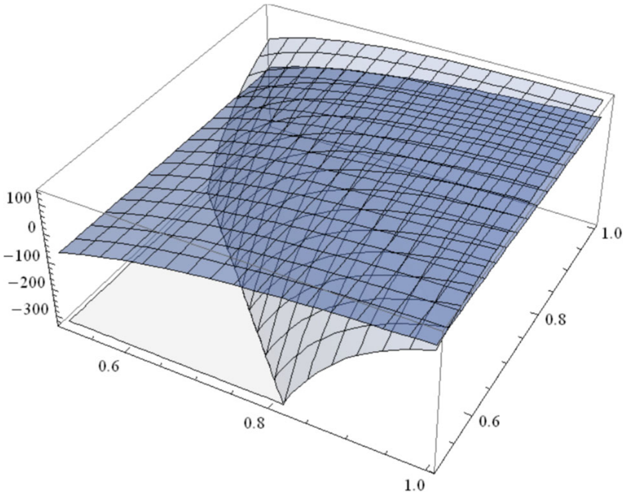


Fig. 6 Order quantity as a function of α and β

Shrinkage-recovery threshold ($\bar{\boldsymbol{\delta}}$)

E-RFID yields a higher order quantity than N-RFID case when $\delta \geq \bar{\delta}$:

$$\bar{\delta} = \frac{\lambda_1^2(p+g) + \sqrt{\lambda_1^4(p+g)^2 - 4\lambda_1^2(c+t)[\lambda_1(p+g-s) - c + s\alpha}}{2[\lambda_1(p+g-s) - c + s\alpha](1-\alpha)} - \frac{\alpha}{1-\alpha}$$

Tag-cost threshold ($\bar{\boldsymbol{t}}$)

Similarly, there exists a tag-cost limit below which RFID adoption increases optimal order quantity:

$$\bar{t} = \lambda_1(p+g) - \frac{1}{\lambda_1^2}(\alpha + \delta(1-\alpha))^2[\lambda_1(p+g-s) - c + s\alpha] - c$$

Figure 6 illustrates the variation of the optimal order quantities in N-RFID and E-RFID cases as the availability coefficients α (shrinkage) and β (misplacement) vary. The two horizontal axes represent α and β while the vertical axis represents the optimal order quantity (expressed in units). The surface shows that, although one would typically expect lower order quantities under E-RFID implementation due to reduced waste and better inventory visibility, it may be optimal to order more when the tag cost is sufficiently low and the shrinkage recovery rate is sufficiently high. In such cases, the improved product availability justifies a larger order, compensating for the additional tagging cost. However, for perishable products, excessively high order quantities are undesirable due to limited shelf life and the risk of spoilage. Therefore, the economically feasible region lies where α and

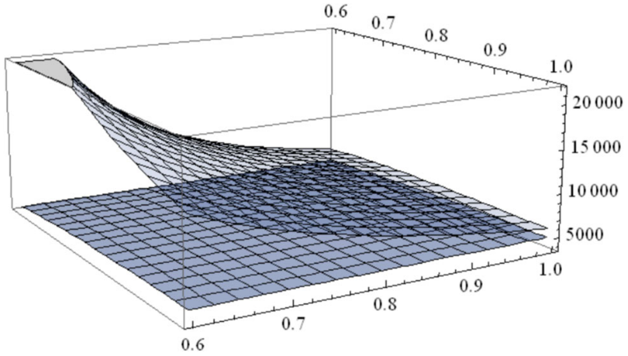


Fig. 7 Profit as a function of α and β

β assume intermediate values, indicating moderate shrinkage and misplacement, and where RFID adoption provides a tangible reduction in uncertainty without inducing overstocking.

Profit-based thresholds

By comparing total profit with and without RFID, we can also determine when RFID yields higher profit.

Accordingly, the shrinkage-recovery threshold in profit condition is:

$$\overline{\delta} = \frac{c + t - \sqrt{(p+g-s)\left[\left(1 - \frac{c-s(1-\alpha)}{\lambda_1(p+g-s)}\right)\left(p+g-s+\frac{c-s\alpha}{\lambda_1}\right) - g + \frac{g\gamma+2K}{\gamma}\right]}}{(1-\alpha)(p+g)} - \frac{\alpha}{1-\alpha}$$

For given fixed cost K, the tag-cost threshold in profit condition is:

$$\overline{t} = \sqrt{(p+g-s)\left[\left(1 - \frac{c-s(1-\alpha)}{\lambda_1(p+g-s)}\right)\left(p+g-s-\frac{c-s\alpha}{\lambda_1}\right) - g + \frac{g\gamma+2K}{\gamma})\right]} + \lambda_1(p+g) - c$$

For a given tag cost t, the fixed-cost threshold is

$$\overline{K} = \frac{\gamma}{2(p+g-s)}\left[(p+g-\frac{c+t}{\lambda_1})^2 - (p+g-s-\frac{c-s\alpha}{\lambda_1})^2\right]$$

Therefore, when $\overline{t} \leq t$, with $\overline{K} \leq K$ and $\delta \geq \overline{\delta}$, RFID adoption is profitable.

If shrinkage and misplacement are already low (high α and β), RFID may not offset its cost.

The threshold analysis allows decision-makers to quantify the economic feasibility of RFID based on product perishability and cost structure.

Figure 7 shows the variation of total profit with respect to the shrinkage availability (coefficient α) and the misplacement availability (coefficient β), comparing the cases with and without RFID.

Table 3 Cost components

Cost component	Dairy (leader)	Retailer (follower)
Tag cost	$\theta_t t$	$(1-\theta_t)t$
Fixed cost (K)	$\theta_K K$	$(1-\theta_K)K$
Stockout cost	g_M	g_R

The surface demonstrates that when both α and β are low, total profit is negative, since only a small fraction of the ordered products is actually available for sale — losses due to shrinkage and misplacement dominate revenues. Conversely, when α and β are high, the benefits of RFID adoption become marginal: the system already performs efficiently (low shrinkage and misplacement), so the additional RFID costs (both fixed *K* and variable tag cost *t*) may outweigh the improvement in visibility and control. Hence, the graph highlights a profitability region where RFID implementation is justified—corresponding to intermediate values of α and β, where product losses are significant enough to recover the RFID investment.

3.6.1 Decentralised supply chain

In the decentralized configuration, the supply chain operates under a leader–follower Stackelberg structure [56], where the dairy (leader) determines the wholesale price *w*, and the retailer (follower) chooses the order quantity Q_D to maximise its own profit, given *w*. Unlike the centralized case—where total supply-chain profit is maximised collectively—each actor now optimizes its own objective function. The interaction between the two decisions determines the equilibrium outcomes in terms of price, order quantity, and overall profitability.

The fixed and variable RFID costs, as well as stockout costs, are shared between the dairy and the retailer according to predefined fractions as per Table 3.

To ensure profitability for both parties, the wholesale price w must satisfy:

$$\mathrm{s} < c < w < p$$

Where c is the unit production cost, s the salvage value, and p the retail price.

3.7 Decentralised, N-RFID scenario

As in the centralised case, the effective availability rate without RFID is defined by λ_1. The retailer profit function is:

$$\prod_R = p(\int_0^{\infty} \mathrm{x}dF(x) + \int_{\lambda 1 Q_D}^{\infty} (\lambda_1 Q_D - x)\, dF(x) + s\int_0^{\lambda 1 Q_D} (\lambda_1 Q_D - x)\, dF(x) - g_R\int_{\lambda 1 Q_D}^{\infty} (x - \lambda_1 Q_D)\, dF(x) + s(1 - \beta)\, Q_D - w_D Q_D$$

Dairy profit function:

$$\prod_D = w_D Q_D - g_M \int_{\lambda 1 Q_D}^{\infty} (x - \lambda_1 Q_D) dF(x) - cQ_D$$

The retailer maximises profit with respect to Q_D, while the dairy maximises profit with respect to w_D. By solving this Stackelberg game, we obtain the optimal wholesale price and order quantity are:

$$w_D^* = \frac{(p + g - s)c + sg_M\alpha}{p + g_M + g_R - s}$$

$$Q_D^* = \frac{1}{\lambda_1} F^{-1}(1 + \frac{s\alpha - c}{(p + g_M + g_R - s)\lambda_1})$$

3.8 Decentralised, E-RFID scenario

When RFID is implemented, product visibility improves, and the effective availability factor becomes $\lambda_{2.}$ The retailer's profit function becomes:

$$\prod_{R,RF} = p\int_0^{\infty} xdF(x) + (p + g)\int_{\lambda_2 Q_D}^{\infty} \left(\lambda_2 Q_{D,RF} - x\right) dF(x) + s\int_0^{\lambda_2 Q_{D,RF}} \left(\lambda_2 Q_{D,RF} - x\right) dF(x) - (w_{D,RF} + \theta_t) Q_{D,RF} - \theta_K K$$

And the dairy's profit function is:

$$\prod_{D,RF} = w_{D,RF} Q_{D,RF} - g\int_{\lambda 2 Q_{D,RF}}^{+\infty} \left(x - \lambda_2 Q_{D,RF}\right) dF(x) - (c + (1 - \theta_t)t)\, Q_{D,RF} - (1 - \theta_K)\, K$$

The optimal wholesale price and order quantity under RFID are obtained as:

$$w_{D,RF}^* = \frac{(p + g - s)(c + (1 - \theta_t)t) + g(\lambda_2 s - \theta_t t)}{p + g_M + g_R - s}$$

$$Q_{D,RF}^* = \frac{1}{\lambda_2} F^{-1}\left(1 + \frac{\lambda_2 s - c - t}{\lambda_2(p + g_M + g_R - s)}\right)$$

The wholesale price under RFID will be lower than without RFID only if:

$$w_{D,RF}^* < w_D^* when t < \frac{-sg\delta(1 - \alpha)}{(p + g - s)(1 - \theta_t) - g\theta_t}$$

Since RFID improves visibility across the supply chain, the retailer can often afford a lower selling price and still maintain profitability, provided the tag cost t is sufficiently low.

By comparing $Q_{D,RF}^*$ and Q_D^*, threshold values can be determined such that:

$$Q_{D,RF}^* \geq Q_D^* when t < t^*,\ \delta < \delta^*$$

The total profit difference between the two configurations is:

$$B^*(t,\ K) = \prod_{RF}(Q_{D,RF}^*,\ w_{D,RF}^*) - \prod(Q_D^*,\ w_D^*)$$

where $B^*(t,\ K) > 0$ indicates that RFID adoption increases joint profitability.

This occurs when both the tag cost t and the fixed cost K are sufficiently low, given the cost-sharing parameters θ_t and θ_K. Under these conditions, both the dairy and retailer benefit from RFID implementation.

This decentralised modelling framework reveals that, in a Stackelberg-type supply chain, RFID alignment of incentives depends critically on cost parameters. When RFID adoption costs are manageable and traceability provides real shrinkage control, both the dairy and the retailer can increase profits. Conversely, if shrinkage and misplacement are already low, the marginal value of RFID does not justify the investment. This provides answer to RQ3.

3.9 Design of experiments

To test how shrinkage propagates and impacts performance in a decentralized supply chain, we designed a simulation-based experiment leveraging the Taguchi L36 Design of Experiments (DOE) methodology. The analytical model had established threshold conditions under which RFID becomes economically viable (via availability, shrinkage, and tag-cost trade-offs). The DOE allows testing whether these insights hold when dynamics such as perishability, backlog penalties, and stochasticity interact over time. The selected factors and levels (e.g., lead times, costs, uncertainties, safety-stock multipliers, price settings) reflect the main levers that co-determine economic and operational outcomes.

To systematically explore the impact of different parameters and compare N-RFID and E-RFID scenarios under varied conditions, we applied a mixed-level L36 orthogonal array supporting both 2-level and 3-level factors, enabling 36 distinct simulation runs (treatments) across a wide range of parameter settings. It is noteworthy to remark that the Taguchi L36 orthogonal array was selected because the experimental design includes multiple operational and economic factors with 2- and 3-levels. The fractional-factorial L36 structure allows to maintain a balanced representation of factor combinations while enabling estimation of main effects and key interactions with a relatively limited number of simulation runs. Therefore, this DOE enables robustness assessment of RFID effects across varying uncertainty and cost conditions, supporting the generalizability of the results.

This design enables efficient estimation of main effects and key two-factor interactions with reduced computational effort. Data for parameter selection and model calibration were collected through structured interviews and questionnaires submitted to industrial practitioners collaborating on the case study.

In our experiment, we varied eleven factors: two with 2 levels and nine with 3 levels. Table 4 summarizes these factors and their corresponding levels. For each run (row in the L36 array), we set model inputs and executed the simulation over the full 5-year horizon, with daily time steps. Outcome measures included the Net Present Value (NPV) of profit at the dairy, wholesaler, and retailer levels, along with total supply chain NPV. Post-simulation analysis was conducted in Minitab using Taguchi methods. We generated main effects plots and two-factor interaction plots and calculated signal-to-noise (S/N) ratios using the "larger-is-better" criterion to identify NPV-maximizing conditions.

In the above table, lead times (factors A and B) were set at two representative levels, e.g.: "short" might represent a 1-day delivery, and "long" a 2-day delivery, based on realistic transit times in our case. Factors C, D, E capture uncertainties and cost parameters at three levels (for example, three levels of order processing cost, and low/medium/high variability scenarios). Factors F, G, H are the safety stock policy multipliers for each echelon, which were tested at three subjective levels (tuned to low, medium, high buffering in the base-stock policy). Finally, factors J, K, L are the selling prices at each stage, varied a few euro-cents around a base value (these affect the distribution of profit among echelons). The Taguchi L36 orthogonal array we used dictates the specific combinations of these factor levels for each of the 36 runs, ensuring a balanced coverage of the design space. For each experimental run, we collected the resulting NPV for the dairy, wholesaler, retailer, and the total supply chain. After all runs were completed, we analysed the results to determine which factors had the most significant impact on each performance measure, and examined how the E-RFID scenario compared to the N-RFID when tested under the same set of conditions.

4 Case study configuration and simulation results

We simulate a real Irish dairy chain using a calibrated SD model and Taguchi DOE, drawing on Fera et al. (2017). The supply chain is represented by a 3-echelons structure—-dairy, wholesaler, retailer—with each echelon managing its own inventory, forecasting, and ordering logic. The model integrates real-world constraints and uncertainties, including demand variability, perishability, and lead times, and tracks financial performance using NPV of cash flows at each echelon and for the total chain. This mirrors Fera et al.'s approach which positions NPV as a strategic objective function able to capture the strategic impact of supply chain decisions.

Table 5 summarizes the key parameters used in the simulation model for both N-RFID and E-RFID scenarios, calibrated from case data and validated through industry interviews.

The parameters replicate actual supply chain behaviors. Daily demand at the retailer reflects a typical supermarket's milk sales and includes slight seasonal trends, such as increased weekend demand. Under the N-RFID configuration, orders are issued periodically: the retailer orders weekly from the wholesaler, who, in turn, orders biweekly from the dairy. In both scenarios, delivery lead times remain fixed, representing actual processing and transit durations: 3 days from dairy to wholesaler and 1 day from wholesaler to retailer.

Milk perishability is modeled with a 9-day shelf life, as validated in literature [55]. Shrinkage is modeled at 2% per cycle in N-RFID due to handling inefficiencies, whereas in E-RFID it is reduced to 0% due to automation and stock visibility.

Industrial cost data were derived from anonymized industrial sources. Milk production is priced at €0.50 per unit.

Table 4 Factors and levels used in the Taguchi L36 experimental design. Numeric values are shown where explicitly applied; coded levels "low/medium/high" were used in the design for certain factors where exact values are case-specific

ID	Factor	Levels in L36	Unit	Primary response tracked
A	Delivery lead time (dairy)	2 levels	days	NPV (dairy)
B	Delivery lead time (wholesaler)	2 levels	days	NPV (wholesaler)
C	Order cost	0.50; 0.75; 1.00	€/day	NPV (retailer)
D	σ (actual demand)	0.50; 1.00; 2.00	unit/day	Total NPV
E	σ (forecast error)	0.50; 1.00; 2.00	unit/day	Total NPV
F	Safety-stock multiplier (k) (dairy)	low; medium; high	–	(robustness; service/profit)
G	Safety-stock multiplier (k) (wholesaler)	low; medium; high	–	(robustness; service/profit)
H	Safety-stock multiplier (k) (retailer)	low; medium; high	–	(robustness; service/profit)
J	Selling price (dairy)	0.50; 0.55; 0.60	€/unit	NPV (dairy)
K	Selling price (wholesaler)	0.80; 0.85; 0.90	€/unit	NPV (wholesaler)
L	Selling price (retailer)	1.20; 1.25; 1.30	€/unit	NPV (retailer)

Selling prices generate realistic margins across echelons: €0.55 (dairy to wholesaler), €0.85 (wholesaler to retailer), and €1.25 (retailer to consumer). Holding cost is set at 0.194% per day (about 50% annually), and fixed order costs vary as a scenario parameter. Expired units incur full production loss, charged to the holder echelon. In E-RFID, additional costs include a €0.05 tag per unit and an annual infrastructure cost ranging between €1000 and €5000, covering readers, IT systems and maintenance. These are amortized as daily overheads and attributed across the chain. The 5-year simulation horizon captures long-term dynamics, with a 5% discount rate applied for NPV.

Using Minitab, we analysed each simulation run—generated by the L36 Taguchi design—via main-effects plots, two-factor interaction plots, and signal-to-noise (S/N) ratios to identify robust NPV-enhancing conditions. Figures 8, 9 and 10 illustrate the most informative interaction effects per echelon.

For the dairy, NPV is most sensitive to its selling price, while order cost has a smaller, negative influence. Interaction effects are minimal, suggesting isolated policy tuning is adequate. For the wholesaler, NPV benefits from wider price margins and is further improved by lower order costs and forecast error. Interaction effects are still limited. The retailer displays the highest sensitivity. Higher retail price, reduced demand uncertainty, lower order costs, and shorter lead times—paired with moderate safety-stock multipliers—optimize performance. Excessive buffering, however, increases spoilage. These results highlight that E-RFID's gains are most pronounced at the retail level, where uncertainty is highest. Continuous review and high inventory accuracy help mitigate volatility and shrinkage. Table 6 aggregates the comparative results across key KPIs.

The E-RFID scenario improves service levels (99.9% vs. 95%), reduces retail and wholesale inventories by 20–30% and 10–20%, respectively, and cuts expired waste by 50–75%. The bullwhip effect is also significantly reduced (from > 2.0 to ~ 1.1–1.2). In high-control RFID scenarios, the model shows expiry reductions of up to 90%, representing the theoretical upper bound when full information visibility and strict FEFO compliance are achieved. Such results answer RQ1 and RQ2.

5 Discussion

The simulation findings highlight several implications for both theory and practice. This section (i) underscores the operational and sustainability value of E-RFID traceability by referencing experimental insights and the scenario comparison from Table 6, (ii) explores RFID adoption within decentralized supply chains and the coordination mechanisms required, (iii) positions our results within the existing literature, and (iv) outlines avenues for future research.

5.1 Traceability as a driver of sustainable efficiency and coordinated benefits

Results confirm that E-RFID traceability is not just a compliance mechanism, but a strategic tool that simultaneously enhances service levels and reduces waste, particularly in perishable supply chains. Even after accounting for tag and

Table 5 Key simulation parameters and values for the milk supply chain model (base case)

Parameter	N-RFID	E-RFID	Notes
Retailer review period (order frequency)	7 days	Continuous (daily trigger)	N-RFID uses periodic review; RFID uses automated continuous replenishment
Wholesaler review period	14 days	Continuous (daily trigger)	Wholesaler orders from dairy more frequently under RFID (driven by retailer's data)
Delivery lead time: Dairy to DC	3 days	3 days	Physical processing time from dairy to DC
Delivery lead time: DC to Retailer	1 day	1 day	Delivery time from DC to store
Shelf life of milk	9 days	9 days	Time before product expires. RFID enables strict FEFO
Average daily demand (retailer)	100 units/day	100 units/day	Demand is stochastic; mean calibrated to case data
Demand variability	$\sigma \approx$ 10–20% of mean	Same	Random daily fluctuation; forecast error and variability considered in baseline
Inventory accuracy	Inaccurate (shrinkage occurs)	Nearly 100% accurate	N-RFID has manual records and unknown losses; RFID provides real-time accurate counts
Shrinkage rate (avoidable loss)	2% of inventory per cycle	0% (negligible)	Approx. fraction of product lost to misplacement or non-FIFO sales. Eliminated by RFID
Safety stock policy (each echelon)	Buffer stock at echelon (level set via service factor)	Minimal buffer (low or zero)	Baseline holds extra stock as a precaution; RFID scenario assumes leaner stock
Holding cost rate	50% annual $\approx$ 0.194% per day (0.5/258)	Same rate	Charged on inventory value; penalizes excess stock in both scenarios
Fixed order cost	€0.50 / €0.75 / €1.00 per ordering	Same levels	Cost to process a replenishment order. More frequent orders in RFID can increase total slightly
Unit production cost (dairy)	€0.50/unit	€0.50/unit	Assumed constant; used to calculate waste cost
Selling price (dairy to DC)	€0.55/unit	€0.55/unit	Wholesale price of milk (dairy's revenue per unit)
Selling price (DC to Retailer)	€0.85/unit	€0.85/unit	Distributor's selling price (retailer's purchase cost)
Selling price (Retail to Consumer)	€1.25/unit	€1.25/unit	Retail shelf price to consumers
RFID tag cost	N/A (no tags)	€0.05/unit	Additional variable cost
RFID infrastructure cost	N/A	€1000/€5000 per year	Annualized cost of readers and IT systems for RFID
Simulation horizon	5 years(1825 days)	5 years	Length of simulation run for NPV calculation
Discount rate	5% annual	5% annual	To discount cash flows in NPV

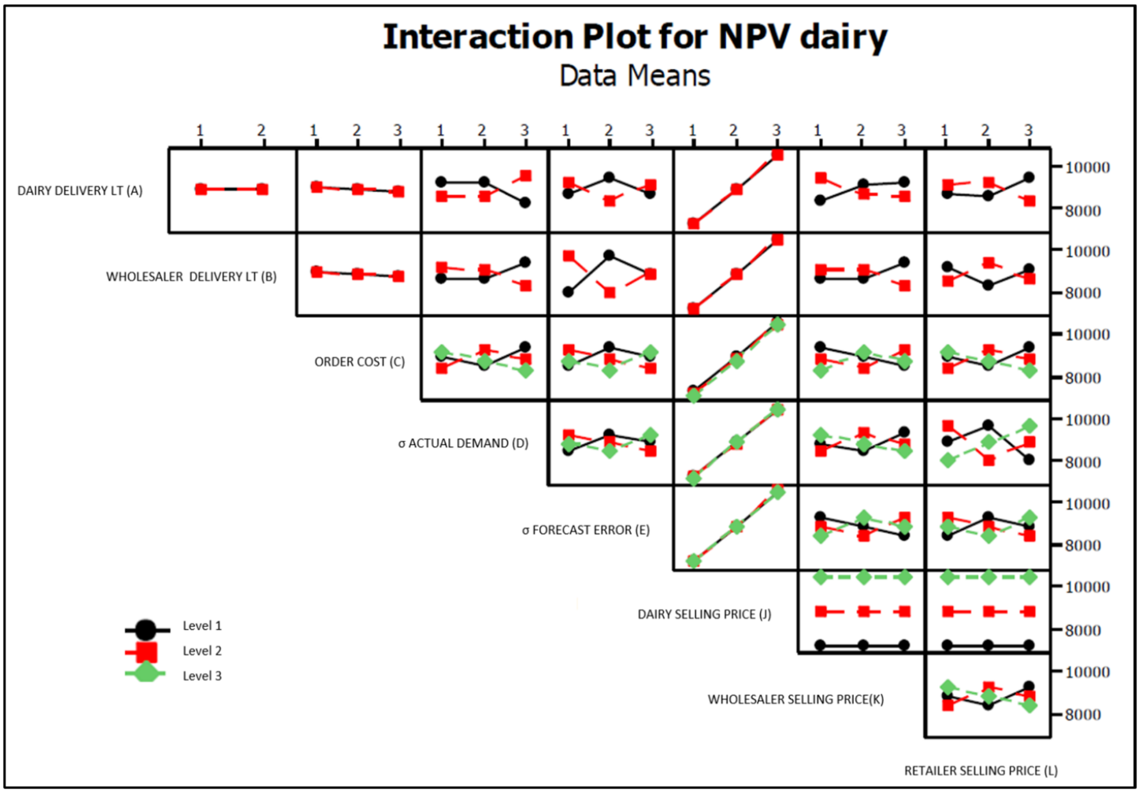


Fig. 8 Interaction Plot for NPV Dairy

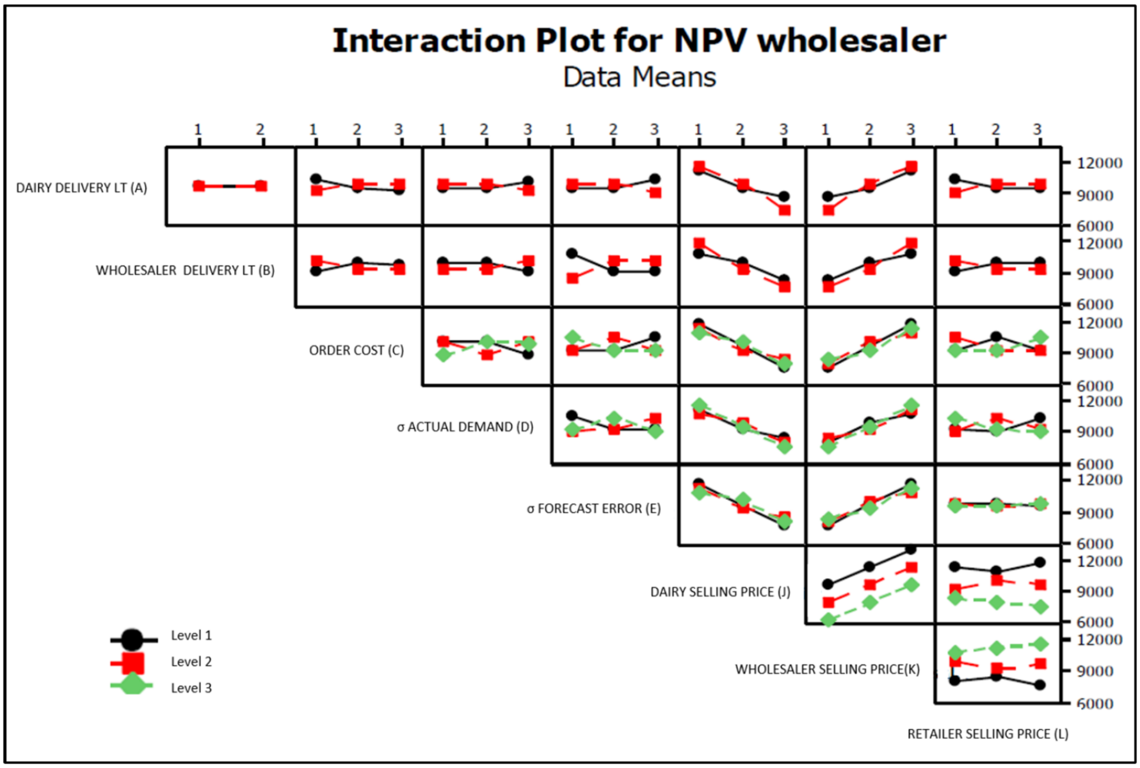


Fig. 9 Interaction Plot for NPV Wholesaler

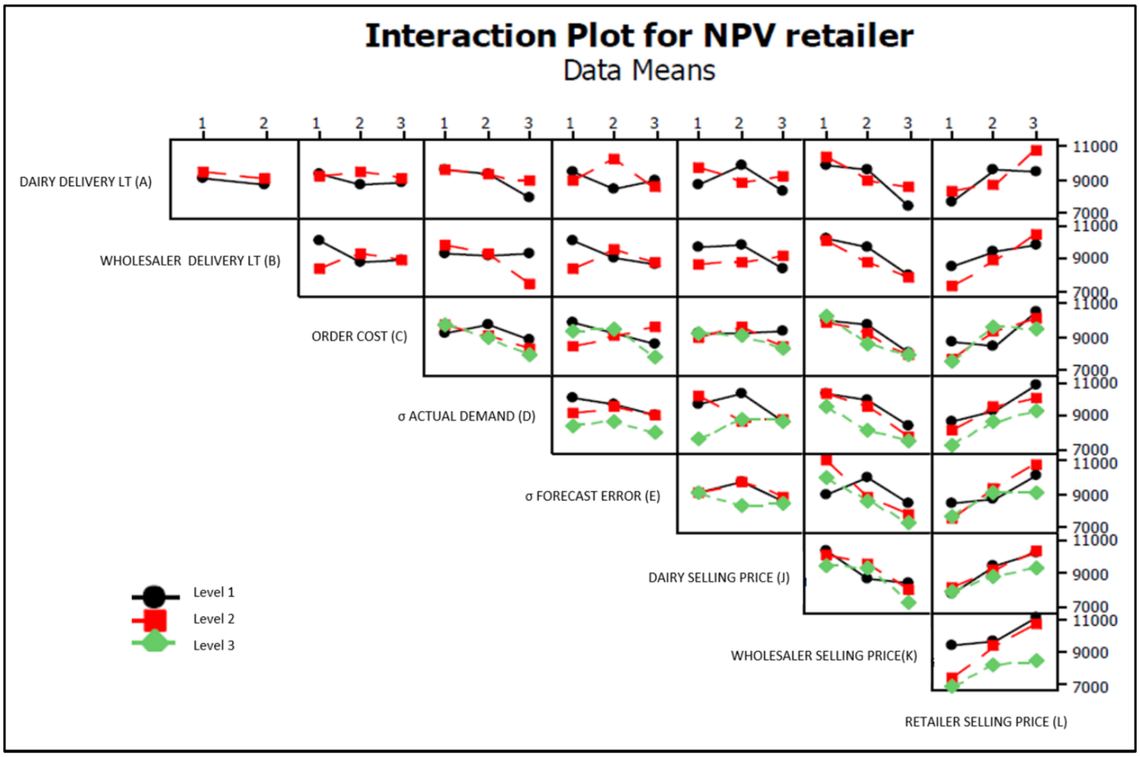


Fig. 10 Interaction Plot for NPV Retailer

Table 6 Performance comparison of baseline vs. RFID scenarios

Metric	N-RFID	E-RFID	RFID scenario performance
Retail service level (fill rate)	95%	99.9%	+ 4.9 percentage points (virtually no stockouts in E-RFID)
Average inventory – Retailer	100% (reference)	70–80% of N-RFID	20–30% lower (leaner stocks)
Average inventory – Wholesaler	100% (reference)	80–90% of N-RFID	10–20% lower (leaner, due to demand visibility)
Total expired waste	5% of units	1–2% of units	50–75% total reduction in waste
Bullwhip ratio	> 2.0 (amplified)	1.1–1.2	Significant dampening of demand variability amplification

infrastructure costs, the E-RFID scenario increases total supply chain NPV by 5–10% over five years, supporting the assumption that visibility reduces waste. This aligns with emerging sustainability narratives in which digital traceability contributes to triple-bottom-line outcomes [18]. Such benefits come from accurate, real-time data management system that allows to eliminate – or, at least, minimise—hidden inefficiencies (e.g., misplacements), support effective FEFO rotation, and allow frequent, tailored replenishments. By reducing uncertainty between supply and demand, RFID delivers both environmental and economic benefits.

While the global system profit increases with RFID, the distribution of gains needs further investigation, since it is often uneven across supply echelons. In our case study, the retailer realizes the largest absolute gains through increased availability and reduced shrinkage. The wholesaler sees moderate improvements, mostly through leaner inventories and fewer emergency actions. The dairy benefits too, but faces a cost burden from tagging that partially offsets its margin increase. In decentralized settings, adoption depends on whether contracts can redistribute part of the RFID-enabled value (e.g., shrinkage reduction and service improvements) to the investing party through measurable, performance-indexed sharing rules. Sensitivity analysis showed that at a €0.05 tag cost, the dairy still gains net-positive results, but if tag costs exceed €0.10–€0.15, the benefits may erode in low-waste conditions. In low-margin perishable supply chains, RFID feasibility thresholds are primarily governed by the balance between shrinkage recovery and tag cost, since waste represents a larger share of total cost. Therefore, adoption is most justified where baseline shrinkage is non-negligible and tag costs remain below the derived thresholds. Coordination contracts are, therefore, essential. Several contract forms have been proposed to realign incentives so that everyone gains. For example, Bai et al. [57] highlight the revenue-sharing and two-part tariffs contracts to split downstream gains while covering upstream tagging costs, also leading to lower carbon emissions. Also, cost-sharing agreements for RFID infrastructure can jointly match interests between upstream payers and downstream beneficiaries [58]. Another solution is to calibrate buy-backs/returns to share overstock risk and hold upstream benefits [45], while E-RFID visibility complements this by preventing waste ex ante.

5.2 Robustness of RFID performance under operational variability

The Taguchi DOE reveals which conditions amplify RFID's advantages. In N-RFID, higher demand variability and forecast error (factors D and E) reduce NPV by increasing buffer sizes or lost sales. In contrast, E-RFID handles these uncertainties better, sustaining higher profits and demonstrating higher S/N ratios. Under high demand variability and forecast error, periodic-review replenishment amplifies delayed demand signals across echelons, generating bullwhip. E-RFID continuous review, instead, transmits consumption information with minimal delay, dampening amplification and stabilizing ordering even in high-uncertainty conditions.

Safety-stock settings further illustrate the difference: raising safety stock improves N-RFID service initially, but erodes profits via higher spoilage. In E-RFID, lean buffers suffice due to accurate visibility. This reflects a structural change in decision coordination: RFID visibility aligns replenishment triggers across echelons around the same real-time consumption signal, whereas periodic review forces each echelon to react independently with safety-stock buffering. The resulting synchronization explains the observed reduction in amplification and inventory levels. Interaction plots show that the profit gap between scenarios widens at higher buffer levels, reinforcing RFID's efficiency.

Delivery lead times (factors A, B) influence both systems, but more so in N-RFID. While RFID doesn't eliminate the impact of transit times, it mitigates their negative effects through immediate response. Still, fast logistics enhance outcomes in both configurations. RFID provides diminishing returns when baseline shrinkage and misplacement are already low and logistics responsiveness is high (e.g., short lead times and efficient replenishment), since the incremental value of additional visibility becomes limited relative to its cost. Holding physical lead times constant isolates the informational and decision-policy effects of RFID-enabled visibility: in practice, RFID adoption may co-evolve with logistics improvements, so combined physical and informational gains are not captured in the present model.

Ordering cost (factor C) marginally affects outcomes. In N-RFID, high order cost deters frequent replenishment, sustaining larger inventories. In E-RFID, more frequent orders are encouraged. Still, the additional cost is offset by lower waste and inventory levels.

Pricing parameters (J, K, L) predictably influence absolute profits. Interestingly, percentage improvements due to RFID are higher in low-margin cases, because waste comprises a larger share of total cost. Across all tested levels, RFID outperforms N-RFID in NPV.

The optimal operational zone features short lead times, low demand uncertainty, minimal forecast error, low order cost, and lean safety-stock policies—conditions most safely approached with RFID visibility.

5.3 Managerial implications and future research

Based on the simulation and DOE findings, several managerial insights emerge:

1) *Prioritize deployment where robustness has the greatest leverage.* The analysis reveals that E-RFID delivers the highest relative benefits under volatile demand, forecasting inaccuracies, and long lead times—conditions typical of perishable categories with chronic stockouts. Moving from periodic to continuous replenishment in such cases improves both profitability and stability, as indicated by higher signal-to-noise ratios. This is consistent with recent work on supply chain resilience and performance mapping under uncertainty [59]. Managers are thus advised to start with high-risk, short-shelf-life products where shrinkage and service failures are measurable and costly.
2) *Treat RFID as a complement to logistics efficiency, not a substitute.* While digital visibility enables rapid decision-making, it cannot compress physical lead times. Fast delivery remains essential, particularly in N-RFID settings. Hence, RFID initiatives should be paired with logistics improvement programs such as cross-docking, more frequent and smaller shipments, or tighter carrier Service Level Agreements. RFID's greatest value emerges when informational and logistical responsiveness are aligned.
3) *Retune policy to translate RFID visibility into performance.* With near-perfect visibility, replenishment logic should shift from periodic to continuous review, and FEFO discipline should become enforceable. Safety-stock multipliers at each echelon can be reduced without compromising service. These changes should be formalized through lowered base-stock targets, shorter reorder cycles, and exception-handling protocols tied to read-rate thresholds, ensuring that information advantages are translated into performance improvements.

4) *Control ordering frequency to optimize efficiency.* Simulation results confirm that inventory savings and waste reduction outweigh added order costs within the tested range (€0.50–€1.00 per order), but diminishing returns exist. An "economic cadence" metric can guide this balance by comparing waste savings to logistics cost increases. When transport costs are high, the optimal order frequency may not lie at the maximum but at a calculated intermediate point.
5) *Prioritize low-margin, short-life products in RFID implementation*. The relative performance gain is amplified when waste and shrink account for a larger share of total costs, as is typical for low-margin dairy and fresh products. Once visibility tools and replenishment practices stabilize in these segments, RFID can be extended to other categories.
6) *Align incentives across echelons to sustain RFID adoption*. While downstream players often reap the most benefit from reduced waste and higher service levels, upstream actors typically bear the technology costs. This imbalance can be addressed through mechanisms such as (i) margin adjustments linked to shrink reduction, (ii) shared infrastructure investments, or (iii) third-party service agreements based on performance metrics. Whichever route is chosen, success hinges on objective, independently verifiable indicators such as fill rates, expiry rates by echelon, bullwhip reduction, and order cadence versus cost.

Based on these principles, a phased RFID deployment path can be outlined. Phase one involves piloting RFID on a focused set of short-life SKUs to enforce FEFO, shift replenishment logic, and safely reduce safety stocks. In phase two, performance gains (e.g., improved fill rates, reduced expiry) are stabilized, and data governance is formalized. Phase three scales the solution to more products and locations, embedding contractual and technical frameworks for benefit-sharing and oversight. Finally, phase four supports continuous optimization, adjusting replenishment thresholds and logistics cadence in response to evolving network conditions and cost structures. Throughout, RFID system accuracy (e.g., read rates) must be monitored to maintain the link between visibility and economic value.

Looking ahead, several research directions can expand managerial relevance and empirical validity. First, modeling imperfect RFID performance—including partial reads and sensor integration—could illuminate tipping points at which benefits fade or intensify. Second, richer operational settings incorporating stochastic delays, capacity constraints, and multi-SKU dynamics would better capture real-world complexity. Third, embedding incentive mechanisms (e.g., revenue sharing, cost allocation, buy-back contracts) as endogenous decisions and testing them through pilot studies or behavioral experiments would strengthen implementation insights. Lastly, combining NPV with environmental impact analysis—by jointly optimizing order frequency, logistics cost, and emissions—would support multi-objective design in perishable supply chains driven by both economic and sustainability goals.

6 Conclusion

This study developed a calibrated system dynamics model of a real Irish three-echelon milk supply chain and applied a Taguchi L36 Design of Experiments to compare two operational scenarios: a baseline with manual, periodic inventory review (N-RFID) and an enhanced RFID-enabled configuration (E-RFID). Across a wide experimental space, RFID-enabled traceability consistently improved operational and financial performance. Key benefits included enforced FEFO rotation, significant reductions in shrinkage and the feasibility of smaller, more frequent replenishment cycles. Simulation results demonstrated notable gains in retail service levels, dampened bullwhip effects, lower average inventories, and substantial reductions in expired waste, especially under high-read-rate, high-discipline RFID settings. In the base case, total supply chain NPV improved by up to 10%, with the largest relative gains observed in low-margin segments and under high uncertainty conditions (demand variability and forecast error). Importantly, RFID should be viewed as a complement, rather than a substitute, for logistics efficiency. While real-time data enhances decision-making, shorter lead times remain universally advantageous. RFID mitigates but does not fully neutralize the disadvantages of longer physical transits. The study also highlighted structural incentive asymmetries in decentralized supply chains. Upstream actors often incur technology and integration costs, whereas downstream actors benefit more directly from waste reduction and improved availability. Mechanisms such as performance-indexed contracts and cost-sharing schemes—anchored in independently verifiable KPIs—can help balance costs and benefits across the network.

Overall, this work advances RFID research in perishable supply chains by integrating system-dynamics modelling, Taguchi experimentation and analytical feasibility thresholds. Also, it contributes by explicitly representing how RFID visibility drives FEFO and continuous-review decisions and their joint effects on waste, inventory, service, and bullwhip. Another relevant contribution was the analysis of decentralized cost–benefit distribution across supply-chain echelons. From a methodological perspective, combining system dynamics with Taguchi DOE proved effective in capturing interactions, assessing robustness, and translating visibility into actionable policy adjustments. Such a methodological integration enabled interpretation of RFID policy performance across uncertainty conditions while preserving dynamic causal structure: while SD explained mechanisms, DOE revealed robustness across parameter regimes. Future research should incorporate imperfect read rates as endogenous system states, enhance operational realism with stochastic constraints and multi-SKU effects, encode contracts as decision rules, and explicitly model the trade-offs between order frequency, transport cost, and environmental impact. Such extensions would strengthen external validity and provide more nuanced managerial insights into RFID adoption in perishable supply chains.

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