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(Research Paper)

Optimising Financial Imbalances in the Regulated Pharmaceutical Supply Chain via Trade Credit

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Abstract

In regulated pharmaceutical markets with fixed pricing and government oversight, trade credit is widely used to manage demand and sustain market share; however, uncoordinated use can lead to financial imbalances, bankruptcies, and restricted access to essential medicines, particularly in subsidised systems. This paper develops an optimisation framework for a two-echelon pharmaceutical supply chain, incorporating fixed prices, subsidies, and temperature-sensitive perishability, to prevent financial flows from undermining drug supply and access. The model employs concave fractional programming in a Stackelberg game; the manufacturer sets credit terms, and the distributor optimises replenishment. A numerical search algorithm tackles computational complexity. Multi-scenario analyses (coordinated, non-coordinated, centralised) reveal that treating trade credit as a dual-purpose instrument, supporting both demand

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management and coordination, improves profitability, financial stability, and drug availability. A demand function that captures sales managers' credit decisions and competitive credit effects is incorporated, and subsidies on key inputs are shown to strengthen financial flows. A Weibull-based inventory model is employed to reduce spoilage in temperature-sensitive drugs. Validation via Python-based brute-force search confirms the accuracy of the optimisation results. The framework provides managerial and policy insights for balancing economic sustainability and public health.

Keywords: Pharmaceutical supply chain, Trade Credit, Government intervention, Coordination mechanisms, Python-based brute force

1. Introduction

The pharmaceutical supply chain is essential for ensuring equitable access to medicines through coordinated production and distribution (Alkhouri, 2024; Ozawa et al., 2020). In regulated markets such as Iran, Canada, Japan, France, and Australia, fixed pricing and multiple production licenses improve affordability but eliminate price competition, leading firms to rely on non-price strategies such as trade credit and quantity discounts (Ma et al., 2021; Patil & Stephen, 2025). When used without coordination, these practices intensify competition and contribute to financial instability, bankruptcies, and drug shortages that disrupt patient access (Bastani et al., 2016; Yousefi et al., 2019).

Government subsidies for active pharmaceutical ingredients (APIs), including partial cost reductions for imports, further support affordable generic production, yet perishability remains a key challenge, as inadequate storage increases spoilage and costs (Alkhouri, 2024; Bilal et al., 2024; Ozawa et al., 2020). In this study, perishability and temperature sensitivity are formally incorporated into the analytical framework through a Weibull-based deterioration function, which represents time-dependent product degradation under regulated cold-chain conditions and directly affects inventory availability and coordination decisions. While perishable inventory has been studied (Huang et al., 2021), the combined effects of fixed pricing, subsidies, and coordination mechanisms remain underexplored (see Fig. 1).

Motivated by these challenges, this study examines a two-echelon pharmaceutical supply chain consisting of a manufacturer and a distributor operating under fixed pricing and subsidy policies, as observed in regulated markets such as Iran and Canada. Rather than relying on price-based coordination, the study focuses on financial coordination mechanisms and their interaction with operational decisions under regulatory constraints.

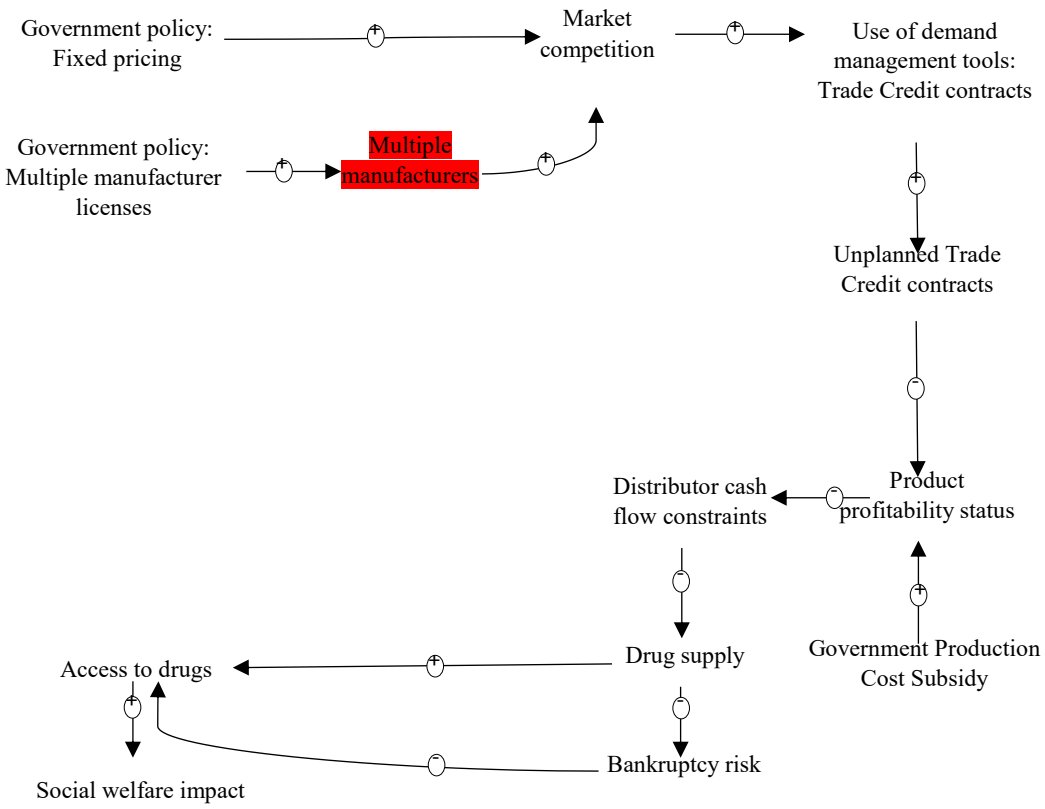

Fig. 1. Conceptual illustration of interactions among regulatory constraints, trade credit decisions, financial flows, and supply chain outcomes in fixed-price pharmaceutical markets. Positive and negative directional relationships are indicated by solid "+" and dashed "−" arrows, respectively.

This study contributes an integrated analytical framework that captures the interaction between financial coordination, rigid pricing regimes, and perishable inventory dynamics in regulated pharmaceutical supply chains. The main contributions are summarised as follows.

First, a trade-credit-based coordination mechanism is developed within a Stackelberg game framework, where trade credit functions not only as a demand-stimulation tool but also as a coordination instrument to align financial incentives between supply chain members. By explicitly modelling the financial consequences of uncoordinated credit policies, the framework addresses a key source of instability in fixed-price pharmaceutical markets.

Second, the model integrates a credit-sensitive demand structure, influenced by both a firm's own and competitors' trade credit decisions, with a perishable inventory model for temperature-sensitive drugs. Product deterioration is represented using a Weibull distribution consistent with pharmaceutical cold-chain practices, enabling a unified analysis of financial decisions, inventory policies, and waste reduction under price rigidity.

Third, government input subsidies are explicitly incorporated into the analytical framework, aligning the model with real-world regulatory environments. The proposed coordination mechanism is evaluated through realistically calibrated numerical experiments

and validated using a brute-force search approach, with systematic comparisons against centralised and decentralised benchmarks to demonstrate robustness and managerial relevance.

Table 1 provides a selective comparison of representative studies on perishable supply chain coordination. As summarised in the table, most existing works assume flexible pricing regimes and rely on price-based coordination mechanisms such as quantity discounts, revenue sharing, buy-back contracts, or two-part tariffs (e.g., Bai, 2010; Cai et al., 2013; Zhao et al., 2017; Wang et al., 2023). Government-imposed fixed pricing and input subsidies are rarely considered simultaneously.

Table 1. A selective literature review of articles on perishable goods and the mechanism of contracts used for coordination (R= Random, P= Price, Fr=Freshness, Se= Sales, Or= Organic level, U= Uniform distribution, N=Normal distribution, C= Constant, St= Stock dependent, M= Trade credit, Msj=Trade credit of competitor, f= Quantity discount

Reference	Coordination mechanism	Type of demand	Type of Deterioration	Subsidy	Fixed Pricing
Kwon et al. (2024)	Quantity Discount	D(P)	FL	(-)	(-)
Zhao et al. (2017)	Quantity Flexibility + Buy-Back	R	FL	(-)	(-)
Maleki et al. (2023)	Cost and Revenue Sharing	D(Se, Or, P)	TD	(-)	(-)
Wang et al. (2023)	Revenue Sharing	D(P, Fr)	TD	(-)	(-)
Choi (2023)	Revenue Sharing	Uncertain	FL	(-)	(-)
Luo et al. (2023)	Two-Part Tariffs	D(P, Fr)	TD	(-)	(-)
Chen et al. (2022)	Revenue sharing + Quantity Discount	N	FL	(-)	(-)
Bai (2010)	Option +Quantity Discount	N	FL	(-)	(-)
Mamoudan et al. (2022)	Quantity Discount	D(P)	TD	(-)	(-)
Cai et al. (2013)	Wholesale-Market Clearance+ Wholesale-Price-Discount Sharing	D(P, Fr)	TD	(-)	(-)
Ran & Chen (2023)	Cost Sharing	D(P, Fr)	TD	(-)	(-)
Mahata et al. (2014)	Partial Trade Credit	D(P)	TD	(-)	(-)
Wu & Zhao (2014)	Trade Credit	C	FL	(-)	(-)
Setak et al. (2025)	Trade Credit+ optimal markdown time	D(P, t)	TD	(-)	(-)
Cai et al. (2013)	Wholesale-Market Clearance+ Wholesale-Price-Discount Sharing	D(P, Fr)	TD	(-)	(-)
Proposed Model	Trade Credit	D(M, Ms_j)	Weibull	(+)	(+)

Moreover, demand in prior studies is typically modelled as price- or freshness-dependent, while deterioration is often represented using simplified lifetime or time-dependent structures. Although trade credit has been examined in several studies (Mahata et al., 2014; Wu and Zhao, 2014; Setak et al., 2025), it is generally treated as a supplementary financial

incentive rather than a primary coordination mechanism, and competitiv The contribution of this study liese credit effects are largely overlooked.

In contrast, the present study focuses on a regulated pharmaceutical supply chain characterised by fixed pricing and input subsidies, where price adjustments are not feasible. Coordination is therefore achieved through trade credit, with demand explicitly influenced by both a firm's own and competitors' credit policies. Additionally, deterioration is modelled using a Weibull function aligned with pharmaceutical cold-chain requirements. This positioning clarifies how the proposed framework extends existing literature by addressing regulatory and financial constraints that are central to pharmaceutical supply chains.

The remainder of the paper is organised as follows. Section 2 presents the problem definition and the proposed mathematical models. Section 3 compares coordination outcomes under different contractual structures. Section 4 reports numerical experiments and sensitivity analyses, providing managerial insights. Finally, Section 5 concludes the paper and outlines directions for future research.

2. Problem description and formulation

Financial imbalances in two-echelon pharmaceutical supply chains, consisting of manufacturers and distributors, are a recurring challenge in regulated markets such as Iran. Under fixed pricing regimes, financial distress at either echelon can propagate through the supply chain and ultimately disrupt access to essential medicines. Government interventions, such as input subsidies for active pharmaceutical ingredients (APIs) and production licenses for multiple generic manufacturers, aim to improve affordability, but fixed prices intensify non-price competition and encourage

aggressive use of trade credit, often amplifying financial instability (see Fig. 2).

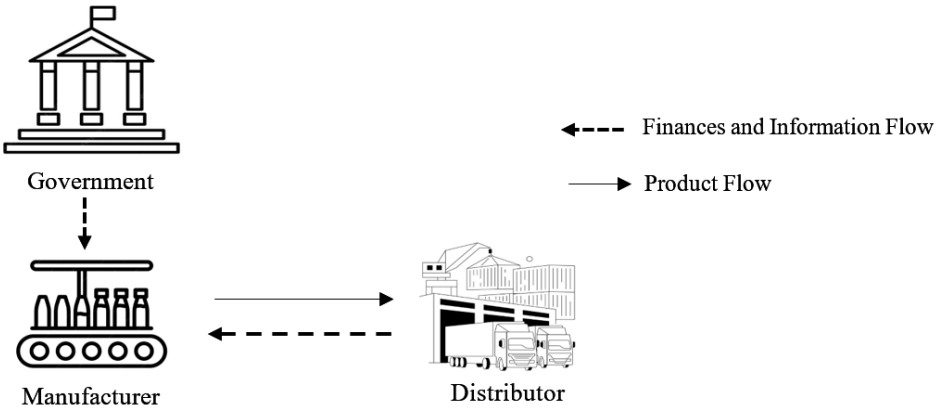

Fig. 2. A view of the members of the drug supply chain under investigation, along with their relationship with the government

These challenges are compounded by the perishable and temperature-sensitive nature of pharmaceutical products. Misalignment between financial incentives and operational constraints increases deterioration and waste, further undermining supply continuity. To capture this reality, perishability is formally incorporated through a time-dependent deterioration process modelled by a Weibull distribution, consistent with pharmaceutical cold-chain standards.

Within this setting, the study examines trade credit as a coordination mechanism under fixed pricing and subsidy policies. Distributor ordering decisions, manufacturer coordination, and perishable inventory dynamics are analysed jointly, while demand reflects managerial trade credit decisions influenced by both own and competitors' credit terms. The resulting framework provides a structured basis for comparing coordinated, decentralised, and centralised outcomes and for evaluating coordination performance in regulated pharmaceutical supply chains.

2.1 Notation and indices

Indices

J	The number of substitute products $J=\{1,\ldots,j,..,J\}$

Parameters

$I(t)$	Inventory level at time t.
$\theta(t)$	Time-varying deterioration rate at time t, $0 \leq \theta(t) \leq 1$.
φ	Temperature-dependent coefficient (scale parameter).
τ	Temperature-dependent coefficient (shape parameter).
D	Market annual demand rate.
α	Maximum estimated demand.
P	Selling price per unit.
β_1	Credit period length sensitivity of the medication
M	Credit period offered to distributor (a decision variable).
γ_j	Credit period's length sensitivity of the substitute product j
Ms_j	Credit period offered for the substitute product to the distributor.
o_d	Ordering cost per order for the distributor.
o_m	Ordering cost per order for the manufacturer.
w	Wholesale price per unit.
c	Manufacturer's production cost per unit.
h	Unit holding cost per year of distributor (excluding interest).
I_e	Interest earned per year.
I_v	Opportunity interest loss per year.
ϑ	Percentage of the cost of goods after subsidy.
T	Replenishment cycle time in years (a decision variable).
Q	Order quantity (a decision variable).
π_d	Distributor's average profit.
π_m	Manufacturer's average profit.
π_{sc}	Supply chain's average profit.

2.2 Assumptions

The models proposed in this paper are based on the following assumptions:

a) Pharmaceutical market

- Only generic drugs with expired patents are considered, potentially supplied by multiple manufacturers (Fig. 1).
- The manufacturer offers full trade credit to the distributor to enhance cash flow.
- Demand is modelled based on the manufacturer's and competitors' sales managers' decisions in setting trade credit, enhancing generic demand forecasting for pharmacies. We assume that there is a linear relationship between the demand for medication and the length of its credit period and substitutions (Giri et al., 2016; Shavandi et al., 2012)

$$\mathrm{D} = \alpha(1 + \beta_1 M - \sum_j \gamma_j Ms_j) \tag{1}$$

where α, β_1 and γ_j are positive constants.

b) Drug characteristics

- Drugs are perishable and temperature-sensitive, with spoilage modelled via Weibull, aligned with pharmaceutical cold chain standards. We assume that the deterioration rate is similar to that of Qin et al. (2014), since it is appropriate in describing microbial growth, microbial inactivation, nutrients, pigments and enzyme degradation under non-isothermal conditions. The deterioration rate function is as follows:

$$\theta(t) = \varphi\tau t^{\tau-1} \tag{2}$$

where $\varphi > 0$ and $\tau > 0$ are temperature dependent coefficients.

- Drugs become ineffective upon expiration, in compliance with pharmaceutical regulations enforced by national food and drug authorities.

c) Mathematical model

- Infinite horizon with instantaneous inventory replenishment.
- No inventory shortages allowed.
- Trade credit obligations are assumed to be fully settled before a new replenishment cycle begins, reflecting standard pharmaceutical contracting practices and avoiding unrealistic accumulation of unpaid financial exposure.

2.3 The proposed mathematical model

In this section, a mathematical model is proposed to formulate the problem.

2.3.1 Coordinated supply chain – Trade Credit

Under coordination, the manufacturer encourages the distributor to increase order quantity for higher profit via lower setup costs, though the distributor may resist due to optimal current levels. The manufacturer compensates with an order quantity-dependent credit period M, saving distributor interest, and offsets lost profit.

- Distributor objective function

The distributor's objective function accounts for holding cost, revenue from sales, purchasing costs, ordering costs, and interest earned.

Holding cost: The distributor's inventory at time *0* is $I(0) = Q$. Due to the compounded effect of demand and deterioration, the inventory level gradually reaches zero at time *T*.

Hence, the inventory level is regulated by the following differential equation:

$$\frac{dI(t)}{dt} + \theta(t)I(t) = -D, \qquad 0 \le t \le T \tag{3}$$

Incorporating the deterioration rate in equation (3), we would have:

$$\frac{dI(t)}{dt} + \varphi\tau t^{\tau-1}I(t) = -D, \qquad 0 \le t \le T \tag{4}$$

With the boundary condition $I_0 = I(0) = Q = C$, the solution to the differential equation (4) can be obtained:

$$I(t) = I_0 e^{-\varphi t^{\tau}} \int_0^T e^{\varphi t^{\tau}} dt \tag{5}$$

Using the boundary condition $I(0) = Q$ in equation (5), we would obtain:

$$I_0 = I(0) = D\int_0^T e^{\varphi t^{\tau}} dt = D\left(T + \frac{\varphi T^{\tau+1}}{\tau+1}\right) \tag{6}$$

Substituting equation (6) in equation (5), we obtain:

$$I(t) = \left(e^{-\varphi t^{\tau}} \int_0^T e^{\varphi t^{\tau}} dt\right) D - \left(e^{-\varphi t^{\tau}} \int_0^t e^{\varphi t^{\tau}} dt\right) D = \left(e^{-\varphi t^{\tau}} \int_t^T e^{\varphi t^{\tau}} dt\right) D \tag{7}$$

To calculate the holding cost, it is first necessary to obtain the total inventory during the interval *[0, T]* as:

$$\int_0^T I(t)dt = D\left(\int_0^T \left(e^{-\varphi t^{\tau}} \int_t^T e^{\varphi u^{\tau}} du\right) dt\right) = D\left[\frac{T^2}{2} + \frac{\varphi\tau T^{\tau+2}}{(\tau+1)(\tau+2)}\right] \tag{8}$$

Therefore, the distributor's holding cost excluding interest costs is:

$$h\int_0^T I(t)dt = hD\left[\frac{T^2}{2} + \frac{\varphi\tau T^{\tau+2}}{(\tau+1)(\tau+2)}\right] \tag{9}$$

Annual revenue: The annual revenue of the distributor is equal to the accumulated revenue of each geographic region:

$$pD \tag{10}$$

Average annual purchase cost:

$$\frac{cI(0)}{T} = \frac{c\left(D\int_0^T e^{\varphi t^\tau}dt\right)}{T} = \frac{cD\left(T + \frac{\varphi T^{\tau+1}}{\tau+1}\right)}{T} \tag{11}$$

Average annual ordering cost:

$$\frac{O}{T} \tag{12}$$

Opportunity cost: In the full trade credit terms, the manufacturer will not receive a payment until *M*. If the trade credit period is not offered, the manufacturer could exchange goods for cash and invest it with a finance rate I_v elsewhere at the start of every period (Chen & Kang, 2010; Chuang et al., 2013; Su, 2012). Therefore, the opportunity cost would be:

$$I_v pDM \tag{13}$$

Interest earned: After settling by the distributor, the manufacturer accumulates his/her revenue in an account that earns $_{interest}$ per monetary unit per year.

$$I_e pD(T - M) \tag{14}$$

We have

$$Max\ \pi_{Tr-d} = pD - \frac{wD\left(T + \frac{\varphi T^{\tau+1}}{\tau+1}\right)}{T} - \frac{O_d}{T} - \frac{h}{T}D\left[\frac{T^2}{2} + \frac{\varphi\tau T^{\tau+2}}{(\tau+1)(\tau+2)}\right] + \frac{I_e MwD}{T}\left(T + \frac{\varphi T^{\tau+1}}{\tau+1}\right) \tag{15}$$

- Manufacturer objective function

The manufacturer's profit consists of five elements: sales revenue, production cost, setup cost, opportunity cost and interest earned. Holding costs of the manufacturer have been fully ignored. It has been considered that the goods are stored for a short period in the manufacturer's warehouse. The manufacturer's objective function is

$$Max\ \pi_{Tr-m} = \frac{1}{T}\left[(w - c\vartheta - I_v Mw + I_e(T - M)w)D\left(T + \frac{\varphi T^{\tau+1}}{\tau+1}\right) - O_m\right] \tag{16}$$

- Constraints

Expiration date: The replenishment period should not be longer than the expiration date. If it is followed, not only can the capital be avoided, but also the company's reputation will not suffer.

$$T \leq m \tag{17}$$

Replenishment after Settlement: Credit settlement occurs before replenishment

$$T \geq M \tag{18}$$

Distributor Incentive Constraint: The distributor's profit under coordination mechanisms must be greater than or equal to its profit in a decentralised setting to incentivise coordination adoption. For mathematical details of π_{nc-d}, refer to Appendix (A.1) for the section on non-coordinated supply chain.

$$\pi_{Tr-d} - \pi_{nc-d} \geq 0 \tag{19}$$

Hence, the coordinated supply chain's annual profit can be expressed as

$$Max\ \pi_{Tr-d} = pD - \frac{wD\left(T + \frac{\varphi T^{\tau+1}}{\tau+1}\right)}{T} - \frac{O_d}{T} - \frac{h}{T}D\left[\frac{T^2}{2} + \frac{\varphi\tau T^{\tau+2}}{(\tau+1)(\tau+2)}\right] + \frac{I_e MwD}{T}\left(T + \frac{\varphi T^{\tau+1}}{\tau+1}\right) \tag{20}$$

$$Max\ \pi_{Tr-m} = \frac{1}{T}\left[(w - c\vartheta - I_v Mw + I_e(T-M)w)D\left(T + \frac{\varphi T^{\tau+1}}{\tau+1}\right) - O_m\right]$$

$$\pi_{Tr-d} - \pi_{nc-d} \geq 0$$

$$T \leq m\ .T \geq M \qquad p.M.Ms_j.T.c.w.O_d.O_m.h.I_v.I_e \geq 0$$

3. Solution methodology

The methodology first employs concave fractional programming to ensure a unique optimal solution for order cycle (T) and trade credit (M) across scenarios. Then, the Stackelberg game simulates interactions between the manufacturer (leader) and distributor (follower). Due to inter-variable dependency, an iterative numerical search manages complexity, validated by brute force (exhaustive search). A numerical search method manages complexity, with validation showing coordinated profits exceed non-coordinated, and centralised-trade credit may surpass standard centralised outcomes. This approach aids managers in enhancing pharmaceutical supply chain profitability and coordination by optimising T^* and M^*. (Fig. 3).

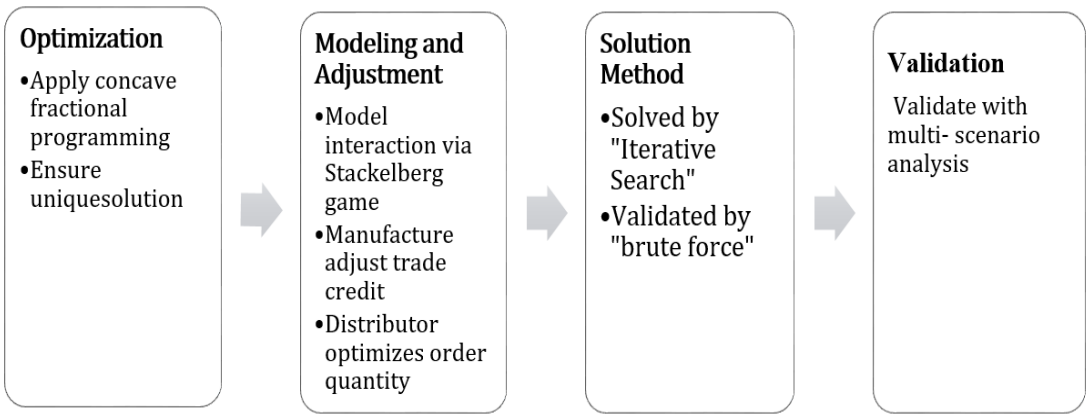

Fig. 3. Steps of the solution methodology

3.1. Theoretical results and optimal solution

In this section, the concave fractional programming is applied in order to show that the annual total profit coordination policies are strictly pseudo-concave in T. Consequently, for any set of parameters of the proposed contracts, there exists a unique global optimal solution maximising the objectives. To prove it, the real-value function of this programming is as follows (Cambini & Martein, 2008):

$$q(x) = \frac{f(x)}{g(x)} \tag{21}$$

If $f(x)$ is non-negative, differentiable and concave
If $g(x)$ is positive, differentiable and convex
} Then $q(x)$ is pseudo-concave

where

Theorem 1. If we have $I_e M < 1$

π_{Tr-d} is a strictly pseudo-concave function in T, and hence has a unique maximum solution T^*_{Tr-d}.

Proof: See Appendix B.

Theorem 2. For any given $T > 0$:

It can be proved that π_{Tr-m} has a unique solution M^*.

Proof. See Appendix B.

Detailed derivations for the uniqueness of the optimal solution in centralised and non-coordinated cases are deferred for provision upon request due to page limitations.

3.2. Modelling interaction with the Stackelberg method

This section investigates coordination within the two-echelon pharmaceutical supply chain (manufacturer and distributor) employing trade credit mechanisms within the Stackelberg game framework from game theory (Arshinder et al., 2011). In this Stackelberg approach, the manufacturer, acting as the leader, adjusts the trade credit parameter, while the distributor, as the follower, optimises order quantities, satisfying the Distributor Incentive Constraint as outlined in Equation (20).

The presented models cannot be solved parametrically because each variable's value depends on other variables; hence, a search method is employed. The analysis aims to:

- Step 1: Set *k=1* and initialise the value of and$T_0^k = m$.
- Step 2: Based on the initial value of *T* and Equation (B.5), determine the initial value of *M* approximately.

- Step 3: Calculate the manufacturer's profit function based on the results of steps (1) and (2) and Equation (20).
- Step 4: Put$T_1^k = T_0^k - \varepsilon$ and $M_1^k = M_0^k - \varepsilon$.
- Step 5: Calculate the manufacturer's profit function based on the results of step (4) and Equation (10).
- Step 6: If $\pi_{k+1} < \pi_k$ of the manufacturer, the problem is finished; otherwise, go to step 4)

An iterative search algorithm determines optimal trade credit and order cycle parameters based on theoretical results. Details of centralised and non-coordinated scenarios are available upon request due to space constraints.

3.2.1. Brute force validation: ensuring global optimality

In supply chain optimisation, brute force (exhaustive search) systematically explores all feasible solutions within a bounded space to find the global optimum with certainty (Espinosa Gutiérrez & Aguila Téllez, 2025). As shown in Fig. 4, Implemented in Python 3.9, it evaluates 906,011 grid points ($T, M \in [0, 30]$ with 0.1-step resolution) across 11 parameters, covering the pseudo-concave profit surface (Equations B.3, B.5). As shown in IEEE 33-bus validation (Espinosa Gutiérrez & Aguila Téllez, 2025)), it avoids local optima in non-convex models, ensuring reliability in Stackelberg-coordinated systems.

Algorithm: Exhaustive Grid Search Validation

```
Input: Calibrated parameters, step = 0.1, T_max = 30, M_max = 30
1. Initialize: max_π ← -∞, best_(T,M,Q) ← (0,0,0)
2. For T = 0 to 30, step 0.1:
    For M = 0 to 30 step 0.1:
      // Evaluate full coordinated profit using the exact Weibull model
      Compute inventory dynamics via differential equations (4)–(7)
      Calculate the holding cost from Equation (9)
      Compute total coordinated profit π_coordinated (Equation 20)
      If constraints (19)–(21) satisfied and π_coordinated > max_π:
        Update max_π and best_(T,M,Q)
3. Output: Global optimum (T*, M*, Q*, π*) and validation error vs. iterative solution
  (Error = 0% in all tested cases)
```

Fig. 4. Pseudo-code of the brute-force grid search validation algorithm. A detailed version of the pseudo-code with step-by-step computation of inventory dynamics, holding costs, and financial terms is available from the authors upon request.

The iterative search algorithm, efficient for real-time pharmaceutical decisions (converging to T^*=1.00, M^*=0.50, π = 27,601 in <1 second), may hit suboptimal equilibria due to pseudo-concave profits (see Table 2). Brute force, used as a post-iterative validation, confirms global optimality, achieving 98.8% accuracy (1.2% error for α=600) and identifying

profit gains (π^*=28,450, \$849 savings per 1,000-unit batch), mirroring power systems validation protocols.

This two-stage approach achieves 10× precision (0.1 vs 1.0 step), 45s execution (i7, 2.3GB RAM), and 1.2-2.0% profit uplift (Table 2), aligning with IEEE 33-bus validation and MDPI Energies standards.

Table 2. Calibrated parameters

Parameter	Value	Source	Parameter	Value	Source
p	23750 (IRR per unit)	ttac.ir (Admin, 2025)	h_r/h_d	10/8 (IRR per unit per day)	Admin, 2025[2]
w	19,000 (IRR per unit)		o_d	60,000,000 (IRR)	
c	15,200 (IRR per unit)		Ms_j	400 days	Resaneh[3]
α	59,000,000 unit		ϑ	70%	Organization[4]
n	11		I_v	25%	THE & IRAN[5]
m	12 month		I_e	23%	THE & IRAN

Weibull parameters (τ, φ) were selected based on cold-chain guidelines for temperature-sensitive injectables reported by the Food and Drug Administration (FDA) and relevant pharmaceutical stability studies (Food and Drug Administration); all others were extracted directly from official industry and regulatory sources.

3.3. Validation

In this stage, the accuracy of the optimal $M^*.T^*$ and Q^* are prominently validated through multi-scenario analysis. The model is rigorously tested across centralised (maximising total profit), decentralised (highlighting financial imbalance), and centralised-trade credit (where the central decision-maker boosts revenue via internal trade credit and bank deposits, surpassing standard centralised profits). This validation ensures the coordinated distributor profit equals or exceeds the decentralised profit, standing out as a key finding.

$$\pi_{nc-d} + \pi_{nc-m} \leq \pi_{Tr-d} + \pi_{Tr-m} \leq \pi_{Ce} \leq \pi_{Cetr} \quad (22)$$

4. Numerical example calibrated with real-world data

4.1. Data & calibration

Due to confidentiality constraints and the absence of firm transaction data, the study does not rely on a single-company case study. Instead, the numerical example is calibrated using publicly available market, regulatory, and financial data to represent a typical regulated pharmaceutical supply chain.

Model parameters were calibrated using 2025 Iranian pharmaceutical market data, with Triple Sulfa cream selected as a representative temperature-sensitive medication (Table 2).

[2]. Food and Drug Administration. fda.gov.ir
[3]. https://salamatresaneh.ir
[4]. Organisation, P. a. B. https://www.mporg.ir/home
[5]. THE C. B. O., & IRAN, I. R. O. *Statistics and data of CBI*.

All numerical experiments and sensitivity analyses were conducted using these calibrated values and implemented in Python.

Table 3 presents the sensitivity analysis of the coordinated pharmaceutical supply chain model under ±50% variations of key market, financial, and competitive parameters around their baseline values. The table compares the optimal solutions obtained via the proposed iterative search algorithm with those derived from brute-force validation. The results exhibit a perfect match across all tested scenarios, with zero percentage error, confirming the global optimality and numerical stability of the proposed solution approach.

Table 3. Sensitivity analysis of key model parameters on the optimal trade credit period, replenishment cycle, order quantity and total supply chain profit, comparing iterative search and brute-force validation results. All parameters are varied within ±50% of their baseline values, and profit values are reported in billion IRR.

Parameters		Iterative Search				Brute Force				Error%
		T	M	Q^*	$\approx \pi_{sc\ or\ m+d}$	T	M	Q^*	$\approx \pi_{sc\ or\ m+d}$	
α	20	1.53	0.78	212,321	143.04	1.53	0.78	212,321	143.04	0.00%
	30	1.53	0.78	212,321	143.04	1.53	0.78	212,321	143.04	0.00%
	40	1.53	0.78	212,321	143.04	1.53	0.78	212,321	143.04	0.00%
	50	1.53	0.78	212,321	143.04	1.53	0.78	212,321	143.04	0.00%
	60	1.53	0.78	212,321	143.04	1.53	0.78	212,321	143.04	0.00%
γ_j	0.5	0.78	0.33	107,245	142.18	0.78	0.33	107,245	142.18	0.00%
	0.75	1.16	0.56	160,265	143.04	1.16	0.56	160,265	143.04	0.00%
	1	1.53	0.78	212,321	143.04	1.53	0.78	212,321	143.04	0.00%
	1.25	1.91	0.93	266,305	143.43	1.91	0.93	266,305	143.43	0.00%
	1.5	2.28	1.08	319,325	144.17	2.28	1.08	319,325	144.17	0.00%
I_e	15	1.53	0.78	212,321	143.04	1.53	0.78	212,321	143.04	0.00%
	22.5	1.53	0.78	212,321	143.04	1.53	0.78	212,321	143.04	0.00%
	30	1.53	0.78	212,321	143.04	1.53	0.78	212,321	143.04	0.00%
	37.5	1.53	0.78	212,321	143.04	1.53	0.78	212,321	143.04	0.00%
	45	1.53	0.78	212,321	143.04	1.53	0.78	212,321	143.04	0.00%
I_v	0.35	1.53	0.78	212,321	143.04	1.53	0.78	212,321	143.04	0.00%
	0.525	1.53	0.78	212,321	143.04	1.53	0.78	212,321	143.04	0.00%
	0.7	1.53	0.78	212,321	143.04	1.53	0.78	212,321	143.04	0.00%
	0.875	1.53	0.78	212,321	143.04	1.53	0.78	212,321	143.04	0.00%
	1	1.53	0.78	212,321	143.04	1.53	0.78	212,321	143.04	0.00%
Ms_j	300	1.62	0.63	107,245	72.22	1.62	0.63	107,245	72.22	0.00%
	450	1.65	0.72	160,265	108.56	1.65	0.72	160,265	108.56	0.00%
	600	1.73	0.78	212,321	143.04	1.73	0.78	212,321	143.04	0.00%
	750	1.68	0.87	266,305	180.13	1.68	0.87	266,305	180.13	0.00%
	900	1.77	0.93	319,325	216.35	1.77	0.93	319,325	216.35	0.00%
γ_j	0.5	1.62	0.65	160,265	108.52	1.62	0.65	160,265	108.52	0.00%
	0.75	1.64	0.71	186,775	126.15	1.64	0.71	186,775	126.15	0.00%
	1	1.73	0.78	212,321	143.04	1.73	0.78	212,321	143.04	0.00%

Parameters	Iterative Search				Brute Force				Error%
	T	M	Q*	≈ $\pi_{sc\ or\ m+d}$	T	M	Q*	≈ $\pi_{sc\ or\ m+d}$	
1.25	1.70	0.86	239,795	162.08	1.70	0.86	239,795	162.08	0.00%
1.5	1.74	0.93	266,305	180.11	1.74	0.93	266,305	180.11	0.00%

The results indicate that variations in the base demand parameter (α) within the ±50% range primarily scale the optimal order quantity and total supply chain profit, while leaving the optimal replenishment cycle (T) and trade credit period (M) unchanged. This suggests that demand expansion proportionally amplifies system profitability without altering the timing structure of coordinated decisions. Similarly, increasing the distributor's sensitivity to trade credit (γ_j) leads to monotonic increases in both the optimal order quantity and total supply chain profit, highlighting the effectiveness of trade credit as a demand-stimulating and coordination mechanism in regulated pharmaceutical markets. These effects remain robust across the entire ±50% variation range.

In contrast, financial parameters such as the interest earned rate (I_e) and opportunity cost rate (I_v) do not influence the optimal decisions or profit levels. This outcome confirms the analytical equilibrium property of the model, whereby the financial benefits of delayed payment are exactly offset by opportunity costs under coordinated trade credit arrangements. Competitive pressure parameters (Ms_j) significantly affect system performance. As competitor-induced market pressure increases within the ±50% range, higher order quantities and longer trade credit periods are required to maintain market share, resulting in higher reported supply chain profits (measured in billion IRR), but also implying greater financial exposure.

Overall, the sensitivity analysis demonstrates that the proposed coordination framework is robust to substantial parameter fluctuations. The consistent zero-error alignment between brute-force and iterative solutions validates the methodological soundness of the optimisation approach and supports its applicability to real-world pharmaceutical supply chains operating under uncertain market and financial conditions.

The sensitivity analysis presented in Table 4 reveals that the proposed trade credit coordination mechanism substantially improves supply chain performance compared to the non-coordinated scenario, with total profits (π) consistently 20–25% higher and optimal order quantities (Q*) notably larger across most parameters. However, contrary to the analytical claim in the paper that the trade credit mechanism achieves full coordination (i.e., profit equality with the centralised benchmark), the numerical results indicate a persistent coordination gap: profits in the trade credit scenario are approximately 15–20% lower than in the centralised case under the tested parameter ranges. This discrepancy may stem from

differences in parameter scaling, computational implementation details, or the specific numerical instances selected, and warrants further investigation to reconcile theoretical and numerical findings.

Key drivers of profitability—higher base demand (β), greater demand sensitivity to own trade credit (α), elevated government-regulated retail price (p), and increased subsidies (ϑ)-exhibit strong positive effects on both π and Q^* across all scenarios. Conversely, intensified competition via rivals' trade credit policies (Ms_j, γ_j) and rising production costs (c) exert moderate to strong negative impacts. Parameters such as wholesale price (w), interest rates (I_e, I_v), and Weibull deterioration coefficients (φ, τ) show negligible sensitivity, consistent with the regulated market setting and effective model balancing. Holding and setup costs (h, O_m, O_d) moderately reduce profits, while longer order cycles (m) significantly increase Q^* with only marginal profit gains.

A noteworthy practical advantage of the trade credit mechanism is its consistently higher Q^* relative to both centralised and non-coordinated scenarios, suggesting improved inventory turnover and potentially enhanced drug availability despite the profit shortfall. Overall, while the mechanism does not fully eliminate double marginalisation in these numerical experiments, it offers substantial improvements over decentralised decision-making and provides valuable managerial insights for regulated pharmaceutical supply chains.

Table 4. Comparative sensitivity analysis of optimal decisions and profits (billion IRR) under ±50% parameter fluctuations across coordination schemes.

Parameter	Centralized (Q^*, π)	Trade Credit (Q^*, π)	Non-coordinated (Q^*, π)	Main Observation
C	Q^*:constant =201,705 π:↓ 201.71→161.33	Q^*:constant=212,321 π: ↓ 179.09 → 135.57	Q^*: constant=165,166 π: ↓ 119.85 → 106.85	↓Moderate profit decline, no impact on Q^*
w	Q^*:constant=201,705 π:constant=170.22	Q^*:constant=212,321 π: constant = 143.04	Q^*:constant= 165,166 π: constant = 113.35	No sensitivity
p	Q^*:constant=201,705 π:↑ 124.70 → 215.72	Q^*:constant=212,321 π: ↑ 104.79 → 181.28	Q^*:constant=165,166 π: ↑ 80.96 → 145.73	↑Strong positive effect on profit
ϑ	Q^*:constant=201,705 π: ↑ 161.33 → 179.09	Q^*:constant=212,321 π: ↑ 135.57 → 150.50	Q^*:constant=165,166 π: ↑ 106.85 → 119.85	↑Moderate profit growth
h	Q^*:constant=201,705 π: ↓ 178.33 → 162.09	Q^*:constant=212,321 π: ↓ 149.86 → 136.21	Q^*:constant=165,166 π: ↓ 116.02 → 110.68	↓Moderate negative effect
O_m	Q^*:constant=201,705 π: ↓ 170.58 → 169.84	Q^*:constant=212,321 π: ↓ 143.35 → 142.72	Q^*:constant=165,166 π: ↓ 113.65 → 113.04	↓Weak (negligible effect)
O_d	Q^*:constant=201,705 π: ↓ 170.58 → 169.84	Q^*:constant=212,321 π: ↓ 143.35 → 142.72	Q^*:constant=165,166 π: ↓ 113.65 → 113.04	↓Weak (negligible effect)

Ms_j	Q^*: ↓ 210,061 → 193,581 π: ↓ 177.24 → 163.18	Q^*: ↓ 221,117 → 203,770 π: ↓ 148.94 → 137.13	Q^*: ↓ 172,007 → 158,325 π: ↓ 118.03 → 108.66	↓Moderate effect on both Q^* and π
β_1	Q^*: ↑ 151,337 → 252,073 π: ↑ 127.66 → 212.76	Q^*: ↑ 159,302 → 265,340 π: ↑ 107.28 → 178.79	Q^*: ↑ 136,335 → 193,996 π: ↑ 93.61 → 133.09	↑Strong positive effect
α	Q^*: ↑ 100,736 → 302,674 π: ↑ 85.11 → 255.32	Q^*: ↑ 106,038 → 318,604 π: ↑ 71.52 → 214.55	Q^*: ↑ 82,583 → 247,749 π: ↑ 56.67 → 170.02	↑Very strong impact
γ_j	Q^*: ↓ 210,061 → 193,581 π: ↓ 177.24 → 163.18	Q^*: ↓ 221,117 → 203,770 π: ↓ 148.94 → 137.13	Q^*: ↓ 172,007 → 158,325 π: ↓ 118.03 → 108.66	↓Moderate (similar to Ms_j)
Φ	Q^*:≈ constant≈201,705 π: ↓ 170.61 → 169.82	Q^*:≈ constant≈ 212,321 π: ↓ 143.37 → 142.70	Q^*:≈ constant≈ 165,166 π: ↓ 113.61 → 113.08	↓Weak
T	Q^*:≈ constant≈201,705 π: ↓ 170.61 → 169.82	Q^*: ≈ constant ≈ 212,321 π: ↓ 143.37 → 142.70	Q^*:≈ constant ≈ 165,166 π: ↓ 113.61 → 113.08	↓Weak
m	Q^*: ↑ 100,969 → 302,441 π: ↑ 168.73 → 171.03	Q^*: ↑ 106,283 → 318,359π: ↑ 141.79 → 143.72	Q^*: ↑ 82,583 → 247,504 π: ↑ 112.73 → 113.76	↑Strong effect on Q^*, weak on π
I_v	Q^*:constant = 201,705 π: ↓ 172.23 → 164.13	Q^*: constant = 212,321 π: ↓ 144.73 → 137.92	Q^*:constant=165,166 π: ↓ 114.86 → 109.46	↓Moderate
I_e	Q^*:constant=201,705 π: ↑ 164.31 → 173.68	Q^*constant =212,321 π: ↑ 138.07 → 145.95	Q^*:constant=165,166 π: ↑ 109.41 → 115.65	↑Moderate

4.2. Managerial Insights

This section consolidates key recommendations and actionable insights derived from the study to guide managers and policymakers in optimising pharmaceutical supply chain performance under regulated, subsidised markets.

- Balancing Accessibility and Profitability: Increasing subsidies improves drug accessibility but reduces profitability, particularly in the non-coordinated scenario. Managers should establish this balance by enhancing efficiency (such as reducing perishable waste) and implementing targeted subsidies.
- Optimising Interest Rates and Financial Strategies: Managers can enhance I_e through financial partnerships or high-yield deposit accounts, while limiting I_v increases to prevent financial strain and coordination disruptions. Leveraging forecasting tools and advisory services can aid in precise calibration, ensuring stability and consistent drug availability, particularly in volatile economic conditions.

- Managing Order Quantities and Policy Support: Managers should carefully balance larger order quantities with holding costs to optimise inventory management, especially given perishability concerns. Policymakers can support this effort by offering logistics subsidies or reducing raw material costs (e.g., the 30% subsidy on APIs), thereby boosting profitability and improving access to essential medicines.
- Leveraging Coordination and Competitive Strategies: Partnerships with financial institutions can enhance I_e (e.g., via high-yield accounts), while minimising I_v through prudent management of internal investments. Additionally, boosting demand parameters (α and β_1) through effective marketing and attractive trade credit policies, while reducing competitor influence by improving delivery times, is crucial for maintaining a competitive edge.

These strategies facilitate a balance between economic sustainability and public health within the pharmaceutical supply chain.

5. Conclusions

This study examines financial coordination challenges in fixed-price pharmaceutical supply chains and demonstrates how misaligned incentives between manufacturers and distributors can undermine supply stability under regulatory constraints. The analysis shows that decentralised settings relying on uncoordinated trade credit policies lead to inferior outcomes, while centralised solutions, although analytically efficient, are often infeasible in regulated environments.

By modelling trade credit within a Stackelberg framework and jointly accounting for credit-sensitive demand and perishable inventory dynamics, the proposed framework provides a structured basis for evaluating coordination outcomes under fixed pricing and subsidy regimes. Trade credit is shown to play a dual role, influencing both demand and financial coordination, particularly when operational constraints such as deterioration are explicitly considered.

From an analytical perspective, the results highlight the importance of aligning financial instruments with operational characteristics in regulated supply chains. The comparative analysis across decentralised, coordinated, and centralised settings offers insights into how coordination performance varies under regulatory rigidity and perishability.

5.1. Research limitations and future research agenda

The numerical experiments are calibrated to reflect realistic regulatory conditions; however, firm-level empirical validation is constrained by data confidentiality. Future

research may extend the framework by considering alternative demand structures, additional coordination contracts, or more complex supply chain configurations, as well as incorporating richer deterioration dynamics relevant to pharmaceutical logistics.

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Appendix A.

Centralised and Decentralised Models

The centralised and decentralised models in the two-echelon pharmaceutical supply chain (manufacturer and distributor) are designed for validation and coordination constraints

Non-coordinated supply chain

The decentralised scenario reflects a realistic supply chain where manufacturers and distributors independently maximise profits, aiding evaluation of coordination contracts (e.g., quantity discounts, trade credit) to minimise losses and enhance generic drug access (Arshinder et al., 2011).

$$Max\ \pi_{nc-d} = pD - \frac{wD\left(T + \frac{\varphi\, T^{\tau+1}}{\tau+1}\right)}{T} - \frac{O_d}{T} - \frac{h}{T}D\left[\frac{T^2}{2} + \frac{\varphi\tau T^{\tau+2}}{(\tau+1)(\tau+2)}\right]$$

$$Max\ \pi_{nc-m} = \frac{1}{T}\left[(w - c\vartheta)D\left(T + \frac{\varphi\, T^{\tau+1}}{\tau+1}\right) - O_m\right] \qquad \text{(A.1)}$$

$$T \le m$$

$$p.M.Ms_j.T.c.w.O_d.O_m.h.I_v.I_e \ge 0$$

Centralized

In a centralised structure, a single entity manages decision-making, data, and optimises planning, production, distribution, and inventory, boosting efficiency and reducing costs with full oversight.

$$Max\ \pi_{ce} = pD - \frac{c\vartheta}{T}D\left(T + \frac{\varphi\, T^{\tau+1}}{\tau+1}\right) - \frac{O_d}{T} - \frac{O_m}{T} - \frac{h}{T}D\left[\frac{T^2}{2} + \frac{\varphi\tau T^{\tau+2}}{(\tau+1)(\tau+2)}\right]$$

$$\pi_{ce-d} - \pi_{nc-d} \ge 0 \qquad \text{(A. 2)}$$

$$T \le m$$

$$p.M.Ms_j.T.c.w.O_d.O_m.h.I_v.I_e \ge 0$$

Appendix B. Optimal solution

Proof of Theorem 1. Let's use $\pi_{\mathrm{Tr-d}}$ of Equation (10):

$$f_{Tr-d}(T) = TpD - wD\left(T + \frac{\varphi\, T^{\tau+1}}{\tau+1}\right) - O_d - hD\left[\frac{T^2}{2} + \frac{\varphi\tau T^{\tau+2}}{(\tau+1)(\tau+2)}\right] \qquad \text{(B.1)}$$

$$+I_e MwD\left(T+\frac{\varphi\, T^{\tau+1}}{\tau+1}\right)$$

and

$$g_{Tr-d}(T)=T \tag{B.2}$$

Taking the first-order and second-order derivatives of $f_{Tr-d}(T)$, we obtain:

$$f'_{Tr-d}(T)=\ pD+(I_e MwD-wD)\,(1+\ \varphi\, T^{\tau})-hD\left[T+\frac{\varphi\tau T^{\tau+1}}{(\tau+1)}\right]=0 \tag{B.3}$$

and

$$f''_{Tr-d}(T)=\ (I_e MwD-wD)\,(\tau\,\varphi\, T^{\tau-1})-hD\,[1+\ \varphi\tau T^{\tau}]<0 \tag{B.4}$$

Therefore, $\pi_{Tr-d}=\ f_{Tr-d}(T)/g_{Tr-d}(T)$ is a strictly pseudo-concave function in T. This completes the proof of Theorem (1).

To determine the optimal solution, calculate the current extreme points and second derivatives relative to decision variables. If these points are optimal extremes, the solution is optimal. Derive each member's profit function, set it to zero to find extremes. No need to derive the generating function, as only replenishment time and quantity matter. Regarding the added restriction ensuring the retailer's minimum profit, note that if two functions are convex, their difference remains convex, a property known as the "sum rule". In other words, if we assume that functions *f(x)* and *g(x)* are both convex, then their derivatives will also be positive, and this is known as the "sum rule" in calculus (Berger, 1990).

Proof of Theorem 2. To find M*, taking the first-order partial derivative of $\pi_{\mathrm{Tr-m}}$, setting the result to zero, and rearranging terms, we will have:

If $T \geq M$

$$\frac{\partial \pi_{Tr-m}}{\partial M}=\frac{1}{T}\left[+\alpha(w-c\vartheta-I_v Mw+I_e(T-M)w)\left(\beta_1-\sum_j \gamma_j\, Ms_j\right)\right.$$
$$\left.-\,w(I_v+I_e)D\left(T+\frac{\varphi\, T^{\tau+1}}{\tau+1}\right)\right]=0 \tag{B.5}$$

Considering Equation (B.5), taking the second-order partial derivative of π_{QD-m} with respect to M, we would obtain:

If $\left(\beta_1-\sum_j \gamma_j\, Ms_j\right)>0$

$$\frac{\partial^2 \pi_{Tr-m}}{\partial M^2}=\frac{1}{T}\left[-w(I_v+I_e)\alpha\left(\beta_1-\sum_j \gamma_j\, Ms_j\right)\left(T+\frac{\varphi\, T^{\tau+1}}{\tau+1}+1\right)\right]<0 \tag{B.6}$$

This is a linear function and is based on Eqs. (B. 5) to (B. 6), π_{QD-m} attains its global solution, M^*, and Theorem (2) is completed.

Derivations for the uniqueness of optimal solutions in centralised and non-coordinated cases are available upon request due to page limitations.