



A Differential Game Theory Approach to Improving Supply Chain Management in Small and Medium Enterprises

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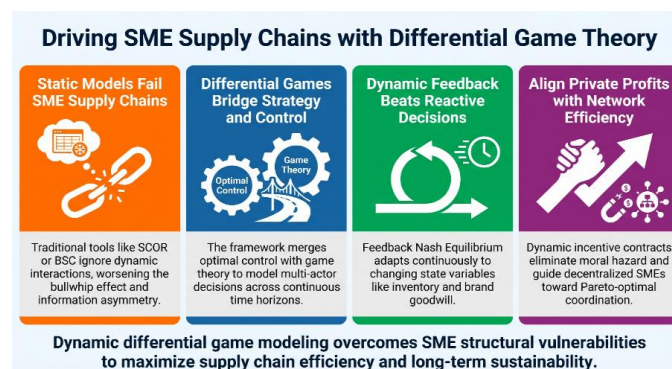
Open Loop.

Abstract:

Effective supply chain management in small and medium-sized enterprises (SMEs) requires strategic decisions that account for resource constraints and competitive interdependence. This study applies differential game theory to improve supply chain decision-making using a mixed-methods approach. Empirical data were collected through questionnaires and semi-structured interviews with managers from 50 SMEs. A dynamic differential game between two competing firms was developed, with capital as the state variable and investment as the control variable. Key parameters included the discount rate, depreciation rate, adjustment cost intensity, competition intensity, and unit investment cost. Open-loop and subgame-perfect Nash equilibrium (SPNE) strategies were compared in terms of investment trajectories, capital accumulation, and profitability, while sensitivity analysis assessed the robustness of the findings.

The results indicate that firms' investment decisions are dynamically interdependent, with each firm's behavior influencing its rival's investment, capital, and profits. The two strategies produce different equilibrium outcomes, while the discount rate, depreciation rate, and competition intensity influence optimal investment policies and profitability. Overall, the proposed framework integrates differential game theory and supply chain management to support long-term strategic decision-making under competition and capital dynamics in SMEs.

Graphical Abstract



1. Introduction

Small and medium-sized enterprises (SMEs) constitute a vital component of global economic systems, making the pursuit of effective operational strategies essential to their sustained development [1]. Within today's increasingly interconnected business landscape, supply chain management has become a central driver of organizational performance and competitive positioning. Nevertheless, SMEs continue to encounter substantial structural and operational obstacles in this domain. On the structural side, they face limited resources, weak bargaining power, and organizational shortcomings compared with larger enterprises [2]. Operationally, they contend with coordination inefficiencies, disputes over cost allocation, pricing complexities, and mounting sustainability demands—difficulties that are further intensified by limited adoption of technology and disjointed supply chain partnerships [3]. As a result, viable supply chain strategies for SMEs must simultaneously overcome these constraints and promote greater adaptability and inter-firm collaboration [4].

Recent global disruptions, including the COVID-19 pandemic and escalating geopolitical tensions, have further highlighted weaknesses inherent in conventional supply chain structures [5]. Given their limited resources and lower resilience, SMEs are especially vulnerable to such shocks, underscoring the need for robust strategic frameworks to ensure their survival and growth. Against this backdrop, differential game theory—a dynamic extension of game-theoretic analysis—has emerged as a powerful mathematical instrument for examining strategic interactions among multiple decision-makers across time [6], offering valuable insight into optimal strategy formation and coordination mechanisms within evolving supply chain relationships [7].

This framework offers three principal advantages. First, regarding temporal dynamics, differential games incorporate time-varying variables and dynamic optimization, overcoming the limitations of static models in capturing continuous decision-making [8]. Second, concerning multi-agent coordination, the approach helps reconcile the diverse objectives of suppliers, manufacturers, distributors, and customers by balancing individual and collective interests [9]. Third, for complex problem resolution, it enables SMEs to model multi-agent interactions through mechanisms such as dynamic cost-sharing contracts, real-time pricing, and sustainable collaboration strategies [10].

Existing research predominantly relies on static frameworks and descriptive case studies that address risk management [11], sustainability and technology adoption [12], and coordination issues [13], and generally lacks rigorous mathematical modeling [14]. Recent developments in supply chain game theory increasingly recognize differential games as a means of capturing temporal and strategic complexity [15], thereby enhancing SME resilience and competitiveness [16].

2. Literature Review

The application of game theory in supply chain management (SCM) has evolved considerably over the past two decades, progressing from static equilibrium analysis toward dynamic decision-making frameworks that capture long-term strategic interactions among supply chain participants. This evolution reflects the growing complexity of supply chains, characterized by uncertainty, information asymmetry, sustainability pressures, and digital transformation. Within this context, differential game theory has emerged as one of the most promising analytical approaches for modeling intertemporal decisions involving investment, coordination, and competition. Recent studies have increasingly emphasized its relevance for small and medium-sized enterprises (SMEs), whose limited resources, organizational flexibility, and vulnerability to disruptions necessitate dynamic rather than static decision models [17, 18].

Comprehensive review studies consistently identify game theory as an increasingly influential methodology for supply chain analysis. Reviews by Gurtu and Johny [2], Bayrak [19], and Rzezycki [20] demonstrate that modern SCM research has gradually shifted from operational optimization toward strategic interaction analysis, highlighting the importance of dynamic and multi-player models for understanding risk, coordination, and organizational resilience [21, 22]. Collectively, these studies argue that traditional optimization methods are often insufficient for representing the adaptive behavior of multiple decision-makers operating in continuously evolving supply chain environments.

One of the dominant research streams focuses on coordination mechanisms and contractual relationships among supply chain members. Static, Stackelberg, and cooperative game models have been extensively employed to investigate pricing policies, inventory decisions, governance structures, and profit allocation. Research has consistently shown that appropriately designed coordination contracts—including revenue-sharing, cost-sharing, buyback, and two-part tariff mechanisms—can substantially improve overall supply chain performance by mitigating double marginalization and aligning incentives among participants [23-26]. Across various industrial settings, collaborative contractual arrangements generally outperform purely competitive structures in profitability, efficiency, and supply chain sustainability [16, 27-29]. Nevertheless, most of these studies examine short-term operational decisions under static assumptions, leaving little room to model the cumulative effects of strategic investments over time. [30]

A second major research direction incorporates sustainability objectives into game-theoretic supply chain models. Increasing environmental regulations, carbon reduction policies, and stakeholder expectations have encouraged researchers to integrate green investment decisions with strategic interactions among firms [31-32]. Differential and cooperative game models have demonstrated that mechanisms such as cap-and-trade systems, environmental subsidies, regulatory penalties, and third-party supervision significantly strengthen firms' incentives to invest in environmentally sustainable technologies while simultaneously improving long-term profitability [33-35]. Similar conclusions have been reported in studies investigating green innovation, quality improvement, and sustainable technology diffusion, where forward-looking strategic behavior enables firms to reconcile economic and environmental objectives [9, 36-39]. These findings illustrate the capacity of dynamic game models to capture gradual processes such as reputation accumulation, technological learning, and sustainability-oriented investments.

More recently, differential game theory has become an increasingly important methodological foundation for analyzing long-term strategic behavior in supply chains. Unlike static games, differential games explicitly account for the evolution of state variables over time, making them particularly suitable for modeling investment dynamics, innovation, knowledge accumulation, pricing, energy management, and collaborative decision-making. Studies by Wang [40], Mu et al. [41], He et al. [42], and Krogmann et al. [43] demonstrate that differential games effectively capture the continuous interactions between competing and cooperating firms operating over extended planning horizons. Similar approaches have been applied to analyze green technology investment, quality improvement, and behavioral adaptation under government regulation [9, 44-45]. Collectively, these studies confirm the superiority of differential games for representing strategic decisions whose consequences unfold gradually rather than instantaneously.

In parallel with sustainability research, digital transformation has generated a rapidly expanding body of literature examining information sharing, omnichannel strategies, blockchain technology, artificial intelligence, and supply chain finance. Researchers have demonstrated that enhanced information transparency through blockchain substantially reduces transaction costs and information asymmetry while improving coordination, particularly for SMEs [17, 46, 47]. Likewise, AI- and machine learning-enhanced game-theoretic models have improved demand forecasting, credit assessment, cybersecurity investment, and operational decision-making under uncertainty [22, 41, 48-51]. Omnichannel coordination, cooperative advertising, and integrated logistics-marketing decisions have also been investigated using dynamic modeling approaches that account for the increasing interdependence between digital and physical supply chain activities [52]. Together, these studies suggest that digital technologies amplify the value of strategic coordination, although their integration within comprehensive dynamic decision frameworks remains limited.

Despite these methodological advances, relatively few studies have explicitly addressed the unique characteristics of SMEs. Compared with large enterprises, SMEs typically operate under tighter financial constraints, limited managerial resources, stronger dependence on strategic partners, and greater exposure to supply chain disruptions [53-58]. Existing research has therefore investigated resilience strategies, cybersecurity investment, disruption management, and risk allocation using differential game models tailored to SME environments [5, 11, 59, 60]. Additional studies have modeled inventory management, pricing, quality decisions, and closed-loop supply chains under various competitive conditions [61-67]. While these contributions introduce greater realism and dynamic complexity, they generally focus on isolated operational problems rather than providing an integrated framework for strategic supply chain performance management in SMEs [68-70].

Systematic reviews consistently identify this limitation as one of the principal research gaps in the current literature. Wu et al. [55], Vasnani et al. [18], Hausken et al. [71], and Shekarian and Flappe [72] conclude that most existing game-theoretic SCM research remains dominated by static or Stackelberg formulations involving relatively few decision-makers and short planning horizons. Moreover, although game theory has demonstrated broad applicability across entrepreneurship, energy systems, digital transformation, and supply chain finance [3, 15, 58], relatively little research has translated differential game outcomes into practical managerial decision frameworks tailored to SMEs. Consequently, the existing literature provides limited guidance on how dynamic strategic interactions can be systematically incorporated into comprehensive performance management models that simultaneously address operational efficiency, long-term investment decisions, and resource constraints. Furthermore, Figure 1 shows that 44 of the reviewed articles were published between 2023 and 2025, highlighting the inclusion of recent research on supply chain management and game theory alongside foundational studies. Furthermore, given the particular importance of interaction structures, cooperation, and time horizons in this study, Figure 2 illustrates the interaction structures, while Figure 3 presents the time horizons identified in the reviewed literature.

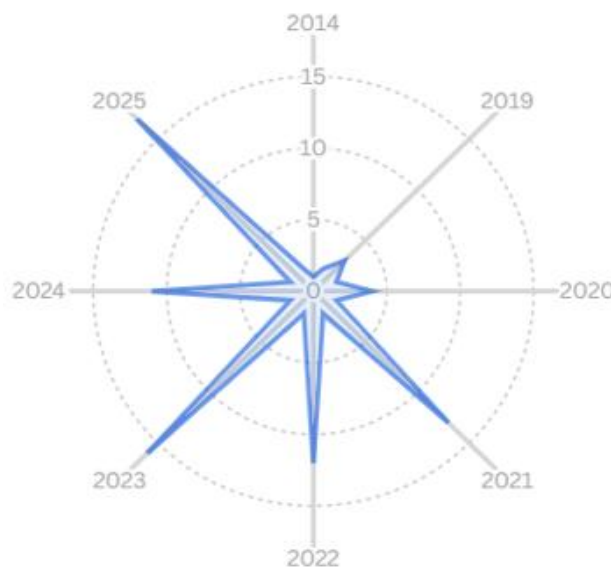


Figure 1. Sources used in this research by year of publication



Figure 2. Categorizing articles based on the structure of interaction and collaboration of games

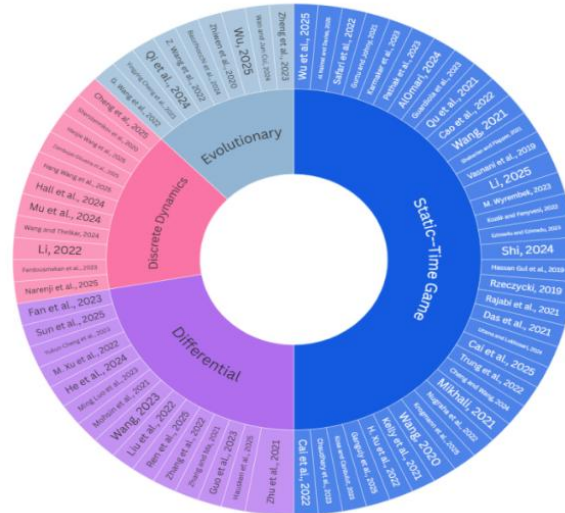


Figure 3. Categorizing articles based on the time horizon of the games (static/dynamic)

To identify research trends and gaps and establish the focus of previous studies, Table 1 presents a matrix-based analysis of the literature, classifying the reviewed studies according to criteria such as review type, time horizon, interaction and cooperation structure, content and application dimensions, and model implementation in SMEs.

Table 1. Categorizing articles based on the model and method used in the supply chain

Title			Number of Articles
Review Articles		Yes	13
		No	59
Time Horizon	Dynamic	Static	36
		Discrete dynamics	11
		Differential dynamics	16
		Evolutionary dynamics	9
		Review Articles	13
Structure of Interaction and Cooperation	Uncooperative	Collaborative	5
		Nash	7
		Stackelberg	15
		Bargaining games	8

	Synthetic	27
	Financial management and pricing	16
	Operations and Logistics Management	21
	Sustainability and Social Responsibility (Green)	14
Content and Practical Dimension	Resilience and risk management	16
	Technology and innovation	16
	Quality and social capital	9
	Other	5
Implementing the Model in SMEs	Yes	13
	No	59

Against this background, the present study seeks to bridge the gap between advanced differential game theory and practical supply chain management in SMEs. Rather than proposing another isolated game-theoretic formulation, this research develops an integrated differential game framework that models dynamic strategic interactions among key supply chain stakeholders and translates mathematical outcomes into actionable managerial decisions. By combining theoretical rigor with practical applicability, the proposed model extends the application of differential game theory from abstract analytical modeling to comprehensive performance management for resource-constrained SMEs operating in dynamic competitive environments.

3. Application of Game Theory in Supply Chain Management

Game theory, a significant branch of applied mathematics, examines strategic interactions among rational decision-makers in which an individual's success is contingent on others' choices. This theoretical framework is designed to analyze relationships between competitors, partners, or potential rivals in complex settings and is built upon three fundamental elements: players, strategies, and payoffs. Structurally, games are classified into two primary categories: non-cooperative and cooperative. In non-cooperative games, players act independently and competitively, whereas cooperative games require collective action to achieve mutual benefits. Furthermore, games are temporally categorized as static (one-shot) or dynamic (multi-stage); in dynamic games, players are informed of each other's previous actions.

A pivotal concept in game theory is the Nash Equilibrium, which denotes a state in which no player has an incentive to unilaterally alter their strategy, given the strategies of the other players. However, this equilibrium is not necessarily collectively optimal, and cooperation can sometimes yield superior outcomes for all involved. This is exemplified by the Prisoner's Dilemma, where individual profit-seeking leads to an inefficient result for the group. In dynamic games, the Subgame Perfect Nash Equilibrium ensures that the selected strategies are optimal at every stage of the game.

For the equitable distribution of payoffs in cooperative games, the Shapley Value is used to calculate each player's share based on their average marginal contribution across all possible coalitions. Zero-sum games represent situations where one player's gain is exactly equivalent to the losses of the others. In contrast, in non-zero-sum games, the potential for creating mutual value exists.

Under conditions of asymmetric information, where some players are deprived of certain information, two types of games play a strategically important role: signaling games (e.g., a manufacturer signaling quality) and screening games (e.g., a buyer designing selection mechanisms). Repeated games facilitate long-term punishment or reward, thereby reinforcing sustained cooperation. Conversely, Bayesian games model uncertainty about other players' characteristics using probability assessments.

Game theory has extensive applications in fields such as supply chain management for Small and Medium-sized Enterprises (SMEs), providing a powerful tool for analyzing issues such as inventory coordination, competitive pricing, and risk-sharing. By transforming conflicts into cooperative opportunities, this theory significantly contributes to optimizing overall system performance.

3.1. Theoretical Framework and Model Specification

From a microeconomic perspective, supply chains can be viewed as decentralized systems in which independent firms make interdependent decisions regarding production, pricing, investment, inventory, and coordination. Because each firm's payoff depends not only on its own decisions but also on the actions of other supply chain members or competing firms, game theory provides an appropriate theoretical foundation for analyzing such strategic interactions. The literature has extensively applied game-theoretic approaches to production and pricing competition, inventory management, supply chain coordination, and contractual relationships.

The Nash equilibrium is a fundamental solution concept in non-cooperative game theory. It represents a state in which each firm's strategy is optimal given the strategies of the other firms, such that no player can improve its payoff by unilaterally deviating. In supply chain settings, Nash equilibrium is particularly appropriate when firms independently determine quantities, prices, investment levels, or other strategic variables. However, because each firm maximizes its own objective, the resulting decentralized equilibrium may differ from the system-wide optimum, creating an important coordination challenge.

Two classical models of competition, Cournot and Bertrand, provide further microeconomic foundations for supply chain analysis. Cournot competition focuses on firms' simultaneous quantity decisions, whereas Bertrand competition emphasizes

price competition. These frameworks have been adapted to supply chains to examine production, capacity, pricing, and competitive interactions among firms and channels.

The Stackelberg equilibrium extends the non-cooperative framework by introducing a leader–follower structure. The leader makes a decision first and anticipates the follower's optimal response. This approach is particularly relevant to vertically structured supply chains in which, for example, a manufacturer determines wholesale terms and a retailer subsequently determines retail decisions. Such models are commonly solved through backward induction and have been widely applied to pricing, inventory, coordination, and channel management problems.

In contrast, cooperative game theory focuses on joint value creation and the allocation of benefits among supply chain members. Concepts such as the core, Shapley value, bargaining solutions, and side-payment mechanisms have been employed to improve coordination and distribute the gains from cooperation.

While these approaches provide important foundations, many supply chain decisions are inherently dynamic because investment, capital, inventory, capacity, and competitive conditions evolve. Differential game theory extends Nash and Stackelberg concepts to such dynamic environments by incorporating state variables and time-dependent control decisions. In particular, open-loop equilibria characterize strategies determined as functions of time and initial conditions. In contrast, feedback or perfect-subgame strategies allow decisions to respond to the system's current state. Differential games have consequently been applied to dynamic supply chain problems in competition, pricing, inventory, capacity, and coordination.

Accordingly, the present study builds on the non-cooperative Nash framework. It extends it, using differential game theory, to capture the dynamic relationships among capital, investment, profitability, adjustment costs, and competitive intensity. The comparison of open-loop and perfect-subgame strategies subsequently provides a basis for evaluating predetermined versus state-dependent decision-making in SME supply chains.

In oligopolistic markets, static models like Cournot (quantity competition) and Bertrand (price competition) provide a valid representation of one-shot, simultaneous-move games. However, as most real-world market competition is repetitive and dynamic, dynamic models offer a more realistic framework. In static models, a firm must make decisions based on conjectures about its rivals' behavior to maximize its profit in a competitive environment. In contrast, in dynamic games, a firm's action can trigger reactions from competitors in subsequent periods.

Although the results derived from the Cournot-Nash equilibrium in one-shot models are insightful, a firm seeking to maximize its long-term profit may achieve a different, non-collusive equilibrium. Recent advancements in game theory have reshaped economists' perspectives on multi-firm markets. Replacing traditional static models with dynamic ones reveals numerous potential equilibria in non-collusive repeated games, some of which arise under competitive conditions.

The prevalence of repeated games in reality invalidates a key assumption of the Cournot model. In such repeated interactions, it is posited that if firm “i” changes its output, firm “j” will react. Therefore, a firm's output in one period, $q_i(t)$ is likely dependent on its output in the next, $q_j(t + 1)$. This temporal dependency cannot exist in a single-period model. For instance, the standard Cournot model assumes $\frac{\partial q_i(t)}{\partial q_j(t)} = 0$, meaning firm “i” believes its rivals will not change their output in response to its own.

The fact that firms may react to one another in a repeated game led to the development of the concept of Conjectural Variation. This concept attempts to incorporate the anticipated reactions of rivals ($\frac{\partial q_j(t)}{\partial q_i(t)} \neq 0$) into a single-period model framework. However, the selection of a specific conjectural variation in a simultaneous, one-shot game can be somewhat arbitrary.

3.2. The Differential Game Model

The model presented in this research formalizes the best response of each firm within a competitive framework. Each firm selects a rule for its production level, representing the optimal quantity it would produce in competition with other firms. The best response function in this dynamic model differs fundamentally from its static counterpart. In a static model, this function represents a single optimal reaction to rivals' output levels, with each output-response pair resulting from a one-dimensional optimization problem. In contrast, the best response function in the dynamic model is derived from an infinite-dimensional optimization process, meaning each firm chooses its response function to maximize its objective function over time.

This study employs a differential game model, a subset of continuous-time dynamic games analyzed using optimal control methods such as the Pontryagin Maximum Principle. Applying this method necessitates several structural assumptions:

Profit and cost functions are specified as quadratic forms, as solutions for such linear-quadratic games are generally tractable. Each player's strategy is assumed to be a continuous function to facilitate the application of optimal control techniques.

A player's payoff at any moment depends on state variables, whose dynamics are governed by a system of differential Equations.

Unlike previous models based primarily on one-shot, non-cooperative games that computed profit and response functions for a single period, the present model incorporates an infinite time horizon. Within this framework, each firm acts to maximize its future profit stream, and its best response function is determined accordingly.

Two distinct strategy types are examined in this game:

Open-Loop Strategy: Players commit to a pre-determined path at the outset, making their best response a function solely of time. The resulting equilibrium in an open-loop differential game is thus expected to resemble the outcomes of static competitive models like Cournot.

Feedback Strategy (Subgame Perfect): This strategy allows players to determine their actions as a function of the current values of the state variables, enabling the application of best response functions even after the game has commenced.

This research focuses on two corresponding equilibria. The primary focus is on the Feedback Nash Equilibrium, which assumes firms select an optimal feedback strategy. Additionally, the Open-Loop Nash Equilibrium is examined under the assumption that firms can pre-commit to an optimal investment path from the outset.

In summary, the Feedback Nash Equilibrium is contingent upon the information available to each player throughout the game. The core analytical findings of this study are revealed by contrasting the Cournot-Nash outcomes under the open-loop and feedback equilibrium regimes. Figure 4 illustrates the extensive-form representation and implementation of the proposed differential game model.

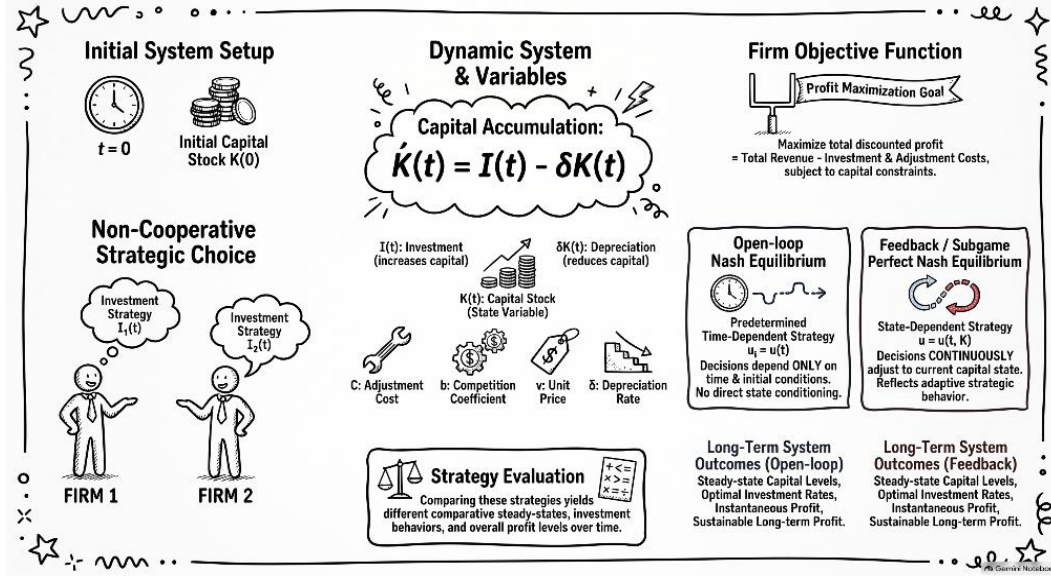


Figure 4. Extensive-form representation of the proposed differential game

3.3. Information Structures

The information structure $\eta_i(t)$ for player "i" is a collection of functions $\{x(s), s \in S(t)\}$, where $S(t)$ is a non-decreasing subset of $[0, T]$.

If $\eta_i(t) = \{x_0\}$, the information structure is open-loop.

If $\eta_i(t) = \{x_0\}, 0 \leq s \leq t$, the information structure is feedback (or subgame perfect).

An open-loop structure is applicable when players cannot observe the state variables after the game begins. In contrast, a feedback structure exists when players can observe and recall the entire history of the state variables. A player's strategy, $\delta_i(\eta_i(t), t)$ defines how they act based on their specific information set. Crucially, because a strategy is defined for a specific information structure, a different Nash Equilibrium will exist for each type of structure.

3.4. Theoretical Framework

The model employed is a differential framework for a duopoly market, selected for its simplicity in analysis and graphical representation. It is predicated on the assumption that the instantaneous profit of each firm is a function of the capital levels of both firms, and each firm may choose to invest or not in the subsequent period. Furthermore, the players possess complete information regarding the game's structure.

Denoting the two firms by indices $i=1,2$, it is demonstrated that the payoff for each firm depends on the investment functions of both. Consequently, for a given $\{I_j(t)\}$, firm i selects $\{I_i(t)\}$ to maximize its objective function, expressed as:

$$V_i = \int_0^{\infty} \Pi_i(K_1, K_2, I_i) e^{-rt} dt$$

Subject to

$$\dot{K}_i = I_i - \delta K_i, \quad K_i(0) = K_{i0}, \quad i = 1, 2$$
(1)

where Π_i represents the instantaneous profit flow, K_i the capital stock of firm "i", I_i the gross investment of firm "i", δ the depreciation rate, and r the discount rate. It is assumed that firms have full knowledge of the game structure and current capital levels, and aim to select an optimal investment path that maximizes discounted future profits.

This section initially focuses on the subgame-perfect Nash equilibrium, and subsequently examines both subgame-perfect Nash and open-loop equilibria.

An open-loop strategy corresponds to a pre-commitment: each firm selects its optimal investment path at the game's outset and cannot alter it thereafter. Each path requires the rival firm to choose the optimal path. However, in the event of random

errors, firms may be inclined to revise their strategies. Consequently, firms typically do not adhere to their pre-commitments and may have incentives to deviate from the announced path.

In the subgame perfect Nash equilibrium, the best response function is selected. The strategy comprises the function $I_i(K_1, K_2)$, which determines the investment level of firm "i" for any given K_1 and K_2 . In contrast, under open-loop equilibrium, the strategy must be optimal for every possible combination of K_1 and K_2 , not merely those along a specific equilibrium path.

3.5. Definition of Strategies

Strategies $(I_1^*(K_1, K_2), I_2^*(K_1, K_2))$ constitute a Nash equilibrium if, for the continuous response functions $J_i: R^2 \rightarrow R$, the following holds:

$$J_1(I_1^*, I_2^*) \geq J_2(I_1^*, I_2^*) \quad \& \quad V_1(I_1, I_2^*) \geq V_2(I_1^*, I_2) \quad (2)$$

for every continuous response function $I_1(K_1, K_2)$ and $I_2(K_1, K_2)$, and for every admissible initial state $K_1(0)$ and $K_2(0)$.

This definition requires that the employed strategies be continuous functions. However, the focus in this model is on the competitive aspects of non-collusive games.

In the model, adjustment costs are assumed to be functions of net investment. Additionally, each firm, due to its monopolistic power, possesses a specific size.

The instantaneous profit function is further assumed to take the form:

$$\Pi_i(K_i, K_j, I_i) = [1 - b(K_i + K_j)]K_i - vI_i - \frac{1}{2}C_i(I_i - \delta K_i)^2 \quad (3)$$

Profit is given by net revenue minus investment costs minus adjustment costs. Net revenue decreases with capital.

In this section, to implement the model, the Pontryagin Maximum Principle is used to solve for both the subgame-perfect Nash and open-loop Nash equilibria. The necessary conditions for both equilibria are stated, and it is shown that an optimal investment solution exists that is linear in the capital level.

Beyond directly solving the optimization problems 1, a variable transformation facilitates computation. If v is the unit price of investment, the discount rate is r , and the depreciation rate is δ , with capital costs expressed as vI_i or $v(r + \delta)K_i$, it can be readily shown that:

$$\int_0^\infty I_i e^{-rt} dt = vK_i(0) + \int_0^\infty v(r + \delta)K_i e^{-rt} dt \quad (4)$$

Thus, the maximization problem transforms to:

$$\text{Max } V_i = \int_0^\infty \left\{ [1 - b(K_i + K_j)]K_i - v(r + \delta)K_i - \frac{1}{2}C_i(I_i - \delta K_i)^2 \right\} e^{-rt} dt \quad (5)$$

Subject to $\dot{K}_i = \tilde{I}_i$

where $\tilde{I} = I - \delta k$ denotes net investment. For brevity, the tilde is hereafter omitted, and I refers to net investment. Additionally, $A = 1 - v(r + \delta)$.

This differential game is solved using the Pontryagin Maximum Principle.

The present-value Hamiltonian is given by:

$$H_i = [A - b(K_i + AK_j)]K_i - \frac{1}{2}C_i I_i^2 + \mu_{i1} I_i + \mu_{i2} I_2 \quad (6)$$

The necessary conditions are thus:

$$\dot{K}_1 = I_1 \quad (7)$$

$$\dot{K}_2 = I_2$$

$$0 = \frac{\partial H_1}{\partial I_1} = -C_1 I_1 + \mu_{11} \Rightarrow \mu_{11} = C_1 I_1 \quad (8)$$

$$0 = \frac{\partial H_2}{\partial I_2} = -C_2 I_2 + \mu_{22} \Rightarrow \mu_{22} = C_2 I_2$$

$$\begin{aligned} r\mu_{11} - \dot{\mu}_{11} &= \frac{\partial H_1}{\partial K_1} = [A - 2bK_1 - bK_2] + \mu_{12} \left(\frac{\partial I_2}{\partial K_1} \right) \\ r\mu_{12} - \dot{\mu}_{12} &= \frac{\partial H_1}{\partial K_2} = -bK_1 + \mu_{12} \left(\frac{\partial I_2}{\partial K_2} \right) \\ r\mu_{21} - \dot{\mu}_{21} &= \frac{\partial H_2}{\partial K_1} = -bK_2 + \mu_{21} \left(\frac{\partial I_1}{\partial K_1} \right) \\ r\mu_{22} - \dot{\mu}_{22} &= \frac{\partial H_2}{\partial K_2} = [A - 2bK_2 - bK_1] + \mu_{21} \left(\frac{\partial I_1}{\partial K_2} \right) \end{aligned} \quad (9)$$

The term $\frac{\partial I_i}{\partial K_j}$ in the above Equations pertains solely to the Cournot-Nash subgame perfect equilibrium. In contrast, for open-loop equilibrium stages, $\frac{\partial I_i}{\partial K_j} = 0$. These Equations contain six unknown parameters: $K_1, K_2, \mu_{11}, \mu_{12}, \mu_{21}, \mu_{22}$.

Given that the problem is linear-quadratic, the solution is tractable. Assume the solution takes the form:

$$\begin{aligned}
\mu_{11} &= \theta_{11}K_1 + \theta_{12}K_2 + \theta_1 \\
\mu_{12} &= \theta_{21}K_1 + \theta_{22}K_2 + \theta_2 \\
\mu_{21} &= \varphi_{11}K_1 + \varphi_{12}K_2 + \varphi_1 \\
\mu_{22} &= \varphi_{21}K_1 + \varphi_{22}K_2 + \varphi_2
\end{aligned} \tag{10}$$

Since the costate variables are linear functions of capital levels, Equations 7 and 10 indicate that investments are also linear in capital, as:

$$\begin{aligned}
I_1 &= (\theta_{11}/C_1) K_1 + (\theta_{12}/C_1) K_2 + \theta_1/C_1 \\
I_2 &= (\varphi_{21}/C_2) K_1 + (\varphi_{22}/C_2) K_2 + \varphi_2/C_2
\end{aligned} \tag{11}$$

Equations 10 involve 12 unknown parameters θ, φ . Substituting the candidate solutions into the differential Equations 7 to 9 yields the coefficients θ, φ .

Moreover, the resulting Nash equilibrium must satisfy the transversality conditions:

$$\lim_{t \rightarrow \infty} \mu_{11} e^{-rt} = \lim_{t \rightarrow \infty} \mu_{12} e^{-rt} = \lim_{t \rightarrow \infty} \mu_{21} e^{-rt} = \lim_{t \rightarrow \infty} \mu_{22} e^{-rt} = 0 \tag{12}$$

From Equations 10, each μ_{ij} converges to a constant if and only if K_1 and K_2 approach constant values. This implies that every equilibrium path, starting from any initial $K_1(0)$ and $K_2(0)$, must converge to the equilibrium point.

The implemented model analyzes competition among actors in the firm's supply chain in the Iranian market, employing game theory in the framework of a differential game. It examines both open-loop and subgame-perfect strategies, deriving the resulting equilibrium points and comparing them.

In the open-loop strategy, decisions are static and committed to at the beginning of the period without subsequent adjustments in response to evolving conditions. In contrast, in the subgame-perfect strategy, decisions are dynamic and depend on the state variables.

In this model, key variables include the discount rate (r), capital depreciation rate (δ), unit price of the good (v), capital production cost (C), firms' competition coefficient (b), steady-state capital level (K), and instantaneous or circulating capital ($I = \delta K$).

State Variable: The capital level of firm i (K_i), representing the system's state at any given moment. It denotes the maximum quantity of product that a unit can produce in a specified period. Since higher production capacity can lead to greater market share, this variable can indirectly indicate the firm's competitive position and is influenced by investment and depreciation.

Control Variable: The firm's investment amount (I_i), serving as a tool through which the firm can control the state variable over time. It also represents the firm's decision regarding new investment levels, which directly affects the state equation. This structure is common in optimal control models and differential games, where firms aim to maximize their objective function by selecting an optimal path for the control variable.

Competition Intensity Coefficient (b): This parameter indicates the firm's market share. Additionally, it reveals the extent to which the rival's capital impacts the firm's profitability.

Adjustment Cost Coefficient (C_i): This parameter represents the holding costs per unit of inventory per month or, in the case of inventory shortages, the average lost cost per unit. Ultimately, the sum of storage costs, capital tie-up, and shortage costs per unit time can be calculated using accounting and logistics data.

Investment Cost Coefficient (v): This parameter represents the actual cost of producing one unit of new capital in relation to the increase in the capital stock.

Discount Rate (r): This parameter was considered constant and was set at 0.23, calculated based on the average inflation rate specific to the respective industry or field of activity.

Depreciation Rate (δ): This index reflects the reduction in capacity or useful life of capital and is calculated from accounting data (annual depreciation relative to asset value).

To implement the proposed differential game model, data were collected from 50 small and medium-sized enterprises (SMEs) operating in different industrial supply chains across Iran. Small and medium-sized enterprises are defined as companies with between 10 and 150 employees. A purposive and convenience sampling strategy was adopted. Initially, 78 small and medium-sized enterprises were identified in the towns and industrial areas of Mazandaran province. After applying the inclusion criteria, 63 companies were considered eligible. Standard questionnaires were distributed to all eligible companies, and 56 were completed and returned. After eliminating 6 incomplete responses, 50 valid questionnaires remained for statistical analysis. As presented in Table 2, The industrial composition of the final sample included food Processing, metal and Machinery Manufacturing, chemical and polymer products companies, and Other Manufacturing Industries, which represent the heterogeneity of the supply chains of small and medium-sized enterprises.

Table 2. Industry composition in the final sample

Industry	Number of Firms	Percentage
Food Processing	11	22 %
Metal and Machinery	8	16 %
Chemical and Polymer	22	44 %

Other Manufacturing	9	18 %
Total	50	100%

The questionnaire consisted of seven sections and 32 measurement items. The first section collected demographic information about the participating firms, including firm size, industry type, years of operation, number of employees, annual sales, and ownership structure. The remaining sections measured the model variables, namely capital stock (K), investment level (I), adjustment cost (C), competition intensity (b), unit price (v), and depreciation rate (δ).

Specifically, capital stock (K) and investment level (I) were measured using financial information obtained from the firms' accounting records and annual financial reports. Adjustment cost (C) was assessed based on inventory adjustment, production adjustment, and operational cost indicators. Competition intensity (b) was measured using four Likert-scale items adapted from previous supply chain competition studies. Unit price (v) was obtained from the average selling price of the firms' main products during the study period, while depreciation rate (δ) was calculated from the firms' annual accounting depreciation records.

Perceptual variables were measured using a five-point Likert scale, ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). In contrast, financial variables were recorded at their actual numerical values, as extracted from company reports.

Table 3 summarizes the operational definition, measurement scale, and data source for each variable used in the proposed differential game model.

Table 3. Operational definition, measurement scale and data source for each variable

Variable	Measurement	Data Source
Capital Stock (K)	Total fixed capital (Billion IRR)	Audited Financial Statements
Investment (I)	Annual capital investment (Billion IRR/year)	Financial Statements
Adjustment Cost (C)	Annual inventory and production adjustment costs (Billion IRR/year)	Accounting Records
Competition Coefficient (b)	Average score of four Likert-scale items (1–5)	Questionnaire
Unit Price (v)	Average annual selling price (Million IRR/unit)	Sales Reports
Depreciation Rate (δ)	Annual depreciation expense / Total fixed assets	Accounting Records

Table 4 presents the number of items in each questionnaire section, while questionnaire reliability was assessed using Cronbach's alpha coefficient. The overall Cronbach's alpha value was 0.87, indicating satisfactory internal consistency. Construct validity was assessed through expert judgment, and all questionnaire items were confirmed to be conceptually consistent with the proposed research framework.

Table 4. Number of items in each section of the questionnaire

Section	Number of Items
General Information about the Enterprise	5
Financial and Capital Information	5
Costs and Production	5
Market Conditions and Competition	5
Investment and Profitability	5
Managerial Attitudes and Strategies	5
Additional Information	2
Total	32

The proposed model was implemented in Python. The implementation process consisted of four consecutive steps:

- 1) Importing and preprocessing the collected questionnaire and accounting data;
- 2) Estimating the model parameters (K, I, C, b, v, and δ);
- 3) Solving the differential game under both open-loop and sub-perfect game strategies using numerical optimization techniques based on the Pontryagin maximum principle;
- 4) Comparing the equilibrium results and performing sensitivity analyses with respect to the discount rate (r), depreciation rate (δ), and competition coefficient (b).

The numerical implementation was validated by verifying the convergence of the equilibrium solutions and comparing the obtained results with the observed financial indicators of the participating firms. Furthermore, sensitivity analyses were conducted by systematically varying the discount rate, depreciation rate, and competition coefficient while keeping the remaining parameters constant, thereby evaluating the robustness of the proposed model. The stability of the numerical solutions was confirmed across all simulation scenarios.

Before estimating the proposed differential game model, descriptive statistics were calculated to summarize the characteristics of the collected data. Table 5 presents the mean, standard deviation, minimum, and maximum values of the main variables. The results indicate noticeable heterogeneity among the participating SMEs, supporting the applicability of the proposed model to firms with different operational and financial characteristics.

Table 5. Mean, standard deviation, minimum and maximum values of the main variables

Variable	Mean	Std. Dev.	Min	Max
Capital Stock (K) (billion IRR)	33.02	4.87	24.33	39.81
Depreciation Rate (δ)	0.168	0.038	0.102	0.249
Unit Price (v) (million IRR)	160.88	74.28	48.48	292.23
Adjustment Cost (C) (million IRR)	16.09	7.43	4.85	29.22
Competition Coefficient (b)	0.111	0.050	0.030	0.183
Working Capital (billion IRR)	2.99	0.47	2.08	3.90

To examine the distributional properties of the collected data, the Shapiro–Wilk normality test was performed for all continuous variables. The results are summarized in Table 6.

Table 6. Examining the distribution characteristics of the collected data

Variable	W	p-value	Result
Capital Stock (K)	0.942	0.0168	Non-normal
Depreciation Rate (δ)	0.951	0.0385	Non-normal
Unit Price (v)	0.922	0.0029	Non-normal
Adjustment Cost (C)	0.922	0.0029	Non-normal
Competition Coefficient (b)	0.942	0.0155	Non-normal
Working Capital	0.954	0.0514	Approximately normal

The Shapiro–Wilk test indicated that most variables were not normally distributed ($p < 0.05$). Therefore, subsequent statistical analyses employed non-parametric methods whenever the assumptions of parametric tests were not satisfied. To investigate the relationships among the main variables, correlation coefficients were calculated before estimating the differential game model.

This approach enabled the evaluation of the performance of different strategies under dynamic conditions and varying parameters, such as depreciation rates and competitive intensity. The validity of the models was confirmed by comparing simulation results with real-world data, using indicators like instantaneous and sustainable profit. Although the study's limitations include a constrained sample size and the incomplete incorporation of macroeconomic factors, the mixed-methods design and advanced analytical tools provide a comprehensive understanding of SME behavior within the supply chain framework.

Given the extensive amount of extracted data and the common limitations in scientific reports, detailed tables for each of the 50 production units have been omitted. Instead, to precisely illustrate firms' strategic behavior and compare the efficiencies of decision-making models, only the average values of key indicators for both strategies are presented in composite tables. This approach maintains content coherence while enabling comparative analysis between dynamic and static models, providing an overall view of the effects of selected strategies on performance management in SME supply chains.

Table 7 reports the mean values of the outputs for each of the indicators listed in the preceding table under the two strategies: open-loop and subgame-perfect Nash equilibrium (SPNE).

Table 7. Comparative Table of Average Indicators for the Two Strategies

Indicator	Open-Loop Strategy	Subgame-perfect Strategy	Percentage Change
Steady-State Capital (K)	25.15	28.77	14.41% Increase
Optimal Investment (I)	4.22	3.88	8.09% Decrease
Instantaneous Profit (Π_{inst})	10.19	14.73	44.5% Increase
Steady-State Profit (Π_{ss})	44	63.94	45% Increase

To determine whether the differences between the Open-loop and Subgame Perfect strategies were statistically significant, a paired-sample statistical test was performed using the equilibrium outcomes obtained for each of the 50 SMEs.

Steady-State Capital (K):

Steady-state capital (K), as the steady-state accumulation of capital and the state variable, indicates the capital level that the supply chain can sustain in the long term. Model interpretation shows that in nearly all sample firms, the subgame-perfect

equilibrium leads to a higher capital level than the open-loop equilibrium. This confirms the superiority of feedback strategies, in which firms' decision-making is a function of the system's current state (existing capital level), and this dependence creates greater incentives to maintain and develop capital infrastructure in the long term. The economic interpretation is that adopting state-dependent strategies reduces investment risk and encourages small and medium-sized enterprises to advance along the path of capital development, resulting in a stronger supply chain infrastructure in the long run.

Optimal Investment (I):

Optimal investment refers to the amount of new capital injected by the firm over a specific time period. Model interpretation suggests that, on average, investment in the open-loop equilibrium is slightly higher than in the subgame perfect equilibrium. This phenomenon can be interpreted as follows: under an open-loop strategy, firms must expend more resources to compensate for their inability to respond to changes in order to maintain their predetermined path. In contrast, the subgame perfect strategy, with its higher K level, exhibits greater investment efficiency and requires less instantaneous investment to maintain the desired steady-state capital level. The economic interpretation indicates that, under subgame-perfect strategies, investment management operates more optimally; resources are allocated based on real needs and current conditions, preventing excessive capital injections, which is critically important for small and medium-sized enterprises with limited resources.

Instantaneous Profit (Π_{inst}):

Instantaneous profit represents the firm's short-term financial performance in the supply chain. As shown in Figure 5, the model results for each firm under both strategies indicate that instantaneous profit is substantially higher under the subgame-perfect Nash equilibrium (SPNE) than under the open-loop strategy. This superiority stems from the fact that subgame-perfect strategies, through optimal adjustments to decisions in each period, can achieve higher productivity from their higher steady-state capital level and provide optimal responses to varying conditions. The economic interpretation is that the flexibility and dynamic responsiveness to market and system conditions (characteristic of subgame-perfect equilibrium) lead to better short-term profitability. This increase in instantaneous profit for small and medium-sized enterprises translates to higher liquidity and operational capacity, laying the groundwork for sustainable growth.

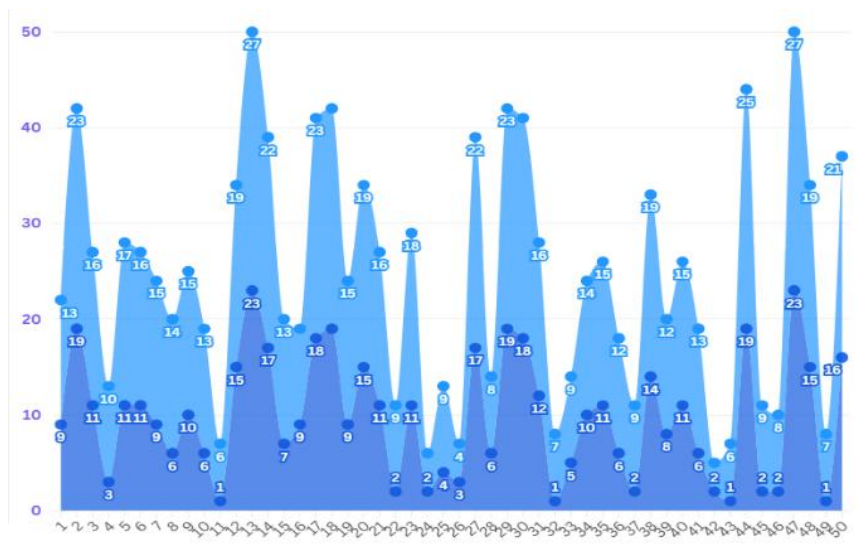


Figure 5. Comparison of Instantaneous Profit for Each Firm and Strategy

Based on the above chart, profit in the "subgame perfect" state is noticeably higher than in the "open-loop" state. This difference arises from the strategic and dynamic nature of subgame-perfect equilibrium, in which firms can adjust their decisions based on competitors' behavior over time. In contrast, in the open-loop strategy, decisions are predetermined and inflexible. Consequently, the flexibility and adaptability of subgame-perfect equilibrium lead to better performance and higher profits for firms, particularly in dynamic competitive environments.

Steady-State Profit (Π_{ss}):

Steady-state profit, as the profit in the steady state, is considered the most important long-term performance indicator for the supply chain. As shown in Figure 6, Model interpretation indicates that steady-state profit in the subgame-perfect equilibrium is markedly higher than in the open-loop state. This result confirms the hypothesis that state-dependent equilibria (such as subgame-perfect equilibria) in differential games yield a higher terminal value than state-independent equilibria (open-loop). The economic interpretation of this finding shows that, to achieve long-term financial sustainability and effective competitiveness in the market, small and medium-sized enterprises must base their supply chain management on the principles of subgame-perfect differential game theory. This strategy, by simultaneously maximizing capital and profit in the long term, ensures the survival and development of these enterprises.

Ultimately, in the open-loop strategy, firms determine their investment path at the outset and do not alter it. Based on the obtained results, this strategy is suitable for stable environments but offers less flexibility. Firms with higher capital exhibited better performance. The positive correlation between capital and profit indicates economies of scale. By contrast, under the subgame-perfect strategy, firms can adjust their decisions based on the current state. This strategy provides greater flexibility

and is better suited to dynamic environments. The significant difference in performance highlights the importance of adaptability to changing market conditions.

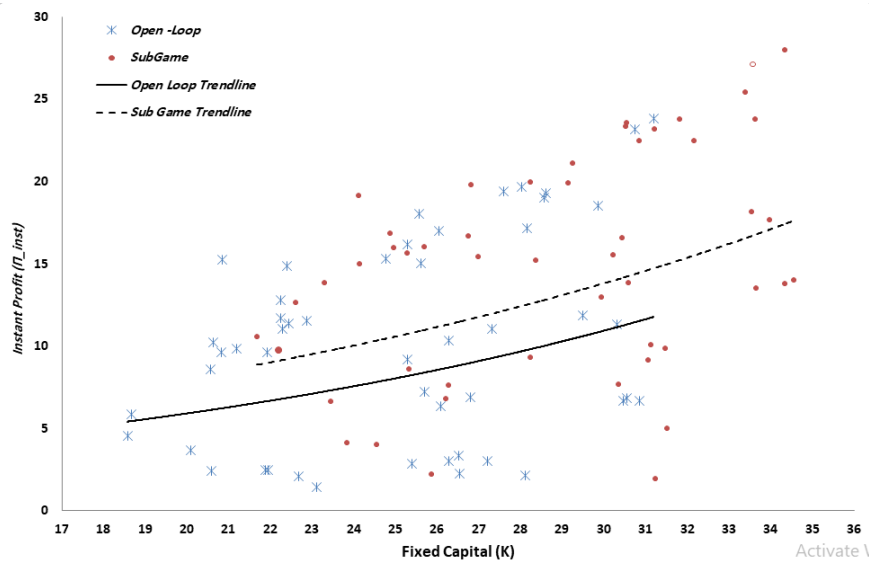


Figure 6. Relationship Between Fixed Capital and Instantaneous Profit (Based on Each Strategy)

Empirical findings indicate a positive but weak correlation between steady-state capital and instantaneous profit under both strategic approaches. In both strategies, a direct and positive relationship between capital and instantaneous profit is observed. Overall, as capital increases (moving rightward on the chart), average instantaneous profit also increases (as indicated by upward trend lines).

The subgame perfect trend line (dashed line) lies above the open-loop trend line (solid line) in most points. This means that under the subgame-perfect strategy (state-dependent), for any given capital amount, the supply chain can, on average, achieve higher instantaneous profits. This superiority demonstrates that if supply chain participants can adjust their decisions based on the current capital state and provide optimal responses at each stage (subgame perfect), chain performance (profit) will be better than when decisions are predetermined without regard to intermediate system states (open-loop).

As shown in Figure 7, it appears that the data point dispersion (variance) for the subgame perfect strategy (red points) is slightly greater than for the open-loop strategy (blue points), particularly at higher capital values. This may indicate that, despite the potential for higher profits in the subgame-perfect strategy, its practical outcomes can be more unstable or sensitive to shocks and momentary operational conditions. The chart suggests that, to maximize instantaneous profit per unit of capital, adopting a subgame-perfect (state-dependent) strategy is preferable to an open-loop (predetermined) strategy. This emphasizes the importance of supply chain flexibility and dynamic adjustments to decisions based on the current state of capital.

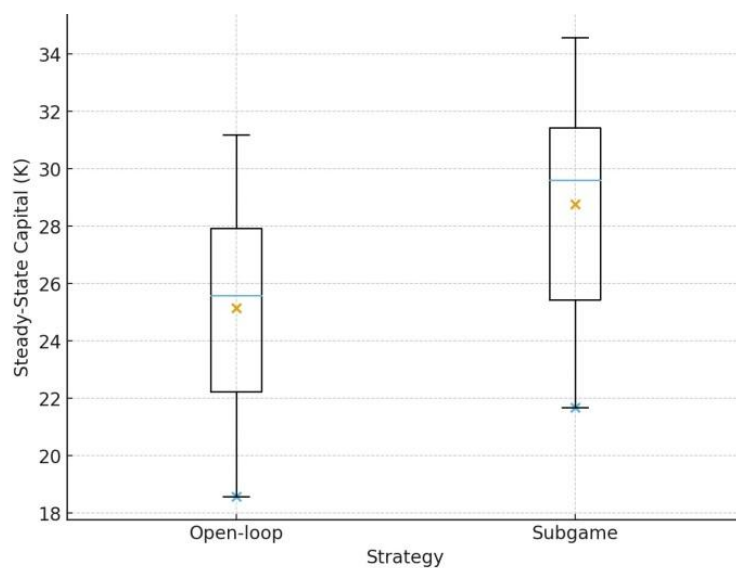


Figure 7. Distribution of Steady-State Capital Based on Each Strategy

Based on the results from the steady-state capital distribution for the two strategies—open-loop and subgame-perfect—it can be observed that the subgame-perfect strategy significantly increases the steady-state capital level in small and medium-sized

enterprises. The average steady-state capital under the subgame-perfect strategy is approximately 28.77, which is notably higher than 25.15 under the open-loop strategy; this indicates that the strategy's emphasis on dynamic and commitment-based decision-making leads to more optimal resource allocation and greater capital sustainability. Furthermore, the mode of steady-state capital—representing the most frequent capital level in the sample population—is 21.68 in the subgame perfect strategy and 18.57 in the open-loop, indicating firms' tendency toward higher capital levels under subgame perfect equilibrium-based strategies. The quartile analysis in the chart also shows that capital distribution under the subgame-perfect strategy is more compact and at higher levels, indicating greater stability and lower volatility than under open-loop. These differences are significant from the perspective of differential game theory, as they demonstrate that implementing policies based on behavioral forecasting and inter-period conditioning can directly enhance the financial sustainability of supply chains in small and medium-sized enterprises.

4. Model Sensitivity Analysis

Based on the sensitivity analysis results presented in Table 8, the behavior of steady-state profit under the two strategies—open-loop and subgame-perfect—with respect to changes in the discount rate (r) reveals different decision-making structures in each approach. In the open-loop strategy, an increase in the discount rate from 0.15 to 0.30 causes a substantial decrease in steady-state profit from 18.45 to 15.12, indicating that this strategy is highly sensitive to discounting future values; since in this structure, firms do not commit to future decision paths, an increase in the discount rate reduces incentives for long-term investment in the supply chain. In contrast, in the subgame perfect strategy, although steady-state profit decreases from 20.67 to 16.28 with the discount rate increase, the slope of decline is less than in the open-loop strategy. This suggests that the presence of inter-period commitments and decisions based on forecasting a counterpart's behavior in subgame-perfect equilibrium mitigates the negative effect of discounting, making steady-state profit levels more resilient to future-value discounting. The profit difference between the two strategies also decreases with increasing discount rate (from 2.22 to 1.16), which from an economic perspective indicates that the relative advantage of the subgame perfect strategy is greater in environments with low discount rates; as the value of long-term decisions and repeated interactions is better realized in such conditions. Overall, the results emphasize that strategies based on subgame perfect equilibrium play a key role in increasing steady-state profit in SME supply chain structures when long-term horizons are highly important.

Table 8. Sensitivity Analysis of Steady-State Profit Relative to Discount Rate (r)

Discount rate (r)	Open-Loop Gain	Subgame perfect Gain	Difference
0.15	18.45	20.67	2.22
0.23	16.73	18.25	1.52
0.30	15.12	16.28	1.16

As presented in Table 9, the sensitivity analysis results show that an increase in the depreciation rate (δ) noticeably reduces the steady-state capital level in both decision-making frameworks: in subgame perfect equilibrium, steady-state capital decreases from 28.24 ($\delta=0.05$) to 18.52 ($\delta=0.12$) (a reduction of about 34.4%), and in the open-loop strategy from 25.67 to 16.89 (a reduction of about 34.2%), meaning the relative reduction effect from depreciation is approximately similar in both cases. However, two noteworthy model-cognitive and economic points stand out: first, subgame perfect equilibrium always maintains a higher steady-state capital level compared to open-loop (difference of 2.57 for $\delta=0.05$, difference of 1.63 for $\delta=0.12$), indicating the positive role of inter-period commitments and competitor behavior forecasting in encouraging long-term investment; second, as δ increases, the gap between the two strategies narrows, meaning the relative advantage of subgame-based mechanisms diminishes in the presence of high capital depreciation because faster depreciation weakens the expected return on investment. From a practical perspective for small and medium-sized enterprises, this finding implies that policies or actions that reduce the effective depreciation rate—such as maintenance and repairs, technology updates, or tax incentives and investment subsidies—can enhance the efficiency of equilibrium-oriented strategies (subgame perfect) and increase enterprises' capacity to sustain steady-state capital; conversely, in environments with high depreciation, the competitive advantage of inter-period commitments diminishes, necessitating a focus on reducing depreciation costs and improving capital productivity.

Table 9. Sensitivity Analysis of Steady-State Capital Relative to Depreciation Rate (δ)

Depreciation Rate	Open-Loop Capital	Subgame perfect Capital	Difference
0.05	25.67	28.24	2.57
0.08	21.31	23.45	2.14
0.12	16.89	18.52	1.63

4.1. Sensitivity Analysis of Instantaneous Profit Relative to Competition Coefficient Parameter (b)

In analyzing the competition coefficient b for each firm, different coefficients were varied while keeping other parameters constant, and its impact on the average and dispersion of instantaneous profit flow was examined. The results showed that as the competition coefficient b increases, firms' average instantaneous profit flow decreases. The primary reason is the form of

the profit function; an increase in b heightens the impact of competition and reduces net revenue. This decrease is observed continuously and nearly linearly in smaller intervals.

The dispersion (standard deviation) also changes with b ; this indicates that the effect of competition is not uniform across firms, and firms with different capital distributions incur losses differently. Therefore, policies such as increasing coordination in the supply chain or long-term contracts can mitigate the negative effects of increased competition.

5. Conclusion

The executed model clearly demonstrates that the subgame perfect strategy holds a significant advantage in the competitive environment of small and medium-sized enterprises in Iran. This strategy, with greater flexibility and adaptability to changing market conditions, leads to higher investment levels and greater profitability. The average 12.3% profit increase in the subgame perfect strategy indicates the high potential of this approach in improving firm performance. Additionally, firms with higher initial capital gained more profit from this strategy, indicating scale effects in the efficiency of dynamic strategies.

Furthermore, the model's sensitivity analysis shows that the advantage of the subgame perfect strategy remains stable under various economic conditions. With an increase in the discount rate, although the absolute difference between the two strategies decreases, the relative advantage of the dynamic strategy persists. Moreover, with increased market competition intensity (increase in parameter b), the importance of flexible strategies grows, and the superiority of subgame perfect intensifies. These findings are crucial for policymakers and managers of small and medium-sized enterprises in Iran, as they demonstrate that investing in dynamic and flexible monitoring systems can yield substantial economic returns. From a policy and managerial perspective, this means that alongside implementing commitment-based strategies (subgame perfect), controlling and protecting capital and reducing negative shocks (e.g., through insurance, incentive contracts, or sustainable financing agreements) is highly important; because in the event of negative shocks, profitability is rapidly undermined.

The results indicate that the subgame perfect strategy performs better for Iranian SMEs operating in volatile environments. The average profit improvement is 12-18%. This finding aligns with differential game theory and the literature on dynamic decision-making. Sensitivity analysis confirms that the superiority of the adaptive strategy remains stable under various conditions.

Ultimately, for small and medium-sized SME enterprises, it is recommended that:

- They invest in information systems and monitoring tools to track key market variables.
- They establish agile decision-making processes that enable rapid responses to changes.
- In relatively stable market conditions, they use the open-loop strategy due to lower costs.

For industries with high depreciation, priority should be given to dynamic and adaptive strategies.

6. Statements & Declarations

6.1. Author Contributions

The following statements should be used:

K.alipour: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization, supervision, project administration, funding acquisition; Y. Gholipour Kanaani, R. Rezaeyan: writing—original draft preparation, writing—review and editing, supervision, project administration. All authors have read and agreed to the published version of the manuscript.

6.2. Availability Statement

The data presented in this study are available in the article.

6.3. Funding

Not applicable.

6.4. Acknowledgments

Not applicable.

6.5. Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this manuscript, the authors used NotebookLM to assist with the review of relevant articles. Following the use of this tool, the authors reviewed and edited the content as necessary and take full responsibility for the content of the published article.

6.6. Ethics Approval

Not applicable.

6.7. Informed Consent

Not applicable.

6.8. Consent for Publication

The author(s) consent to the publication of this manuscript.

6.9. Conflicts of Interest

The author(s) declare no conflict of interest.

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Appendix A

QUESTIONNAIRE

Purpose: This questionnaire collects financial, operational, market, investment, and managerial information from small and medium-sized industrial enterprises for academic research. All information will be treated confidentially. The questionnaire is designed to provide empirical information for estimating the main parameters of the proposed model, including initial capital (K_0), investment (I), investment/adjustment costs (C), depreciation rate (δ), unit selling price (v), competition intensity coefficient (b), and profit-related variables (π).

Section 1. General Information about the Enterprise:

1. Name of enterprise: _____
2. Year established: _____
3. Type of activity: ☐ Manufacturing ☐ Services ☐ Processing and downstream industries ☐ Other: _____
4. Number of employees: _____
5. Target market: ☐ Local ☐ National ☐ Export

Section 2. Financial and Capital Information:

6. Value of fixed capital (billion IRR): _____
7. Working capital (billion IRR): _____
8. Average annual depreciation rate of assets (%): _____
9. Main sources of financing: ☐ Own capital ☐ Bank loans ☐ Foreign investors ☐ Other: _____
10. Change in fixed capital during the past five years: ☐ Decrease ☐ No change ☐ Slight increase ☐ Significant increase

Section 3. Costs and Production:

11. Production cost per unit (IRR): _____
12. Selling price per unit (IRR): _____
13. Cost of production-capacity expansion (billion IRR): _____
14. Annual maintenance and repair costs (billion IRR): _____
15. Equipment renewal/replacement frequency (years): _____

Section 4. Market Conditions and Competition:

16. Number of major competitors: _____
17. Intensity of competition: ☐ Very low ☐ Low ☐ Moderate ☐ High ☐ Very high
18. Competitive strategy: ☐ Price ☐ Quality ☐ Advertising ☐ Innovation ☐ Other: _____
19. Estimated reduction in market share if a new competitor enters the market (%): _____
20. Dependence on key customers: ☐ Very low ☐ Low ☐ Moderate ☐ High ☐ Very high

Section 5. Investment and Profitability:

21. Annual investment during the past three years (billion IRR): _____
22. Annual net profit (billion IRR): _____
23. Return on Investment (ROI) (%): _____
24. Preferred use of excess liquidity: ☐ Reinvestment ☐ Saving ☐ Debt repayment ☐ Other: _____

25. Investment outlook for the next three years: ☐ Decrease ☐ Remain stable ☐ Slight increase ☐ Significant increase

Section 6. Managerial Attitudes and Strategies:

Please rate each statement from 1 to 5, where 1 = Strongly disagree and 5 = Strongly agree.

26. We are conservative in our financial decision-making. ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

27. We are willing to take risks when making new investments. ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

28. Competition encourages us to increase our investment. ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

29. Liquidity constraints are a major barrier to our expansion. ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

30. We prefer short-term profits over long-term returns. ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Section 7. Additional Information:

31. What is the most important current challenge facing your enterprise? _____

32. What types of government or institutional support would be most effective for your enterprise? _____

Appendix B

The numerical implementation of the proposed differential game model was developed using Python 3.11. Numerical optimization was performed using the SciPy package, while NumPy was employed for matrix operations and Pandas for data management. The implementation consisted of five sequential stages: (1) importing the collected SME data; (2) estimating the model parameters; (3) solving the Open-loop Nash equilibrium; (4) solving the Subgame Perfect Nash equilibrium; and (5) conducting statistical and sensitivity analyses.