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A Framework Of Hybrid System Dynamics And Agent Based Model With Cooperative Game Theory For Sustainable Coffee Supply Chain

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ABSTRACT
The global coffee supply chain is a complex network involving diverse stakeholders such as farmers, traders, exporters, and consumers, each with unique incentives and constraints. This study introduces a conceptual framework that integrates System Dynamics (SD), Agent-Based Modelling (ABM), and Cooperative Game Theory (CGT) to address challenges in profit allocation, coalition stability, and sustainability. SD provides macro-level insights into global trends such as price fluctuations and production dynamics, while ABM models individual decision-making processes. CGT complements these methods by facilitating fair payoff distribution and stable coalition formation. The framework is structured into problem identification, model development and mapping, and interaction mode selection, offering a comprehensive approach to understanding material, information, and decision flows. Using illustrative scenarios, the study demonstrates the framework's potential to analyses trade-offs and long-term impacts on supply chain stability. Its practical implications could support policymakers and industry leaders in designing fair profit-sharing mechanisms, promoting stable cooperation among stakeholders, and enhancing the overall sustainability of coffee and other agri-food supply chains. Thus, the framework highlights its applicability as a conceptual tool for supporting decision-making and sustainability in coffee supply chains and beyond.
Keywords: *Agent-Based Model, Coffee Supply Chain, Cooperative Game Theory, Hybrid Simulation, System Dynamics.*

1. Introduction
1.1 Background

Coffee is a vital global commodity, supporting millions of smallholder farmers and serving as a key export for developing countries. The global coffee market is highly volatile, influenced by international traders and economic shifts that create disparities among producers (Ngure & Watanabe, 2024). Indonesia, a major coffee-producing country, has seen its coffee exports play a crucial role in improving its economy (Sayuti & Raza, 2018). Coffee farming provides a substantial source of income for these farmers. Coffee production such as Indonesia is primarily dominated by small farmers, with about 2 million smallholders involved in coffee farming across the archipelago (Faradillah et al., 2019). However, the coffee industry has faced challenges, such as the "coffee crisis," which has led to changes in the governance and institutional arrangements of the coffee commodity chain (Lima & Lee, 2023).

Over time, export concentration has increased, with a few countries dominating the green coffee trade (Kadigi et al., 2022), exacerbating inequality (Utrilla-Catalan et al., 2022). Smallholder farmers, who form the backbone of coffee production, face persistent challenges such as price volatility (Borrella et al., 2015), limited access to high-value markets, and threats from climate change, pests, and diseases (Bracken et al., 2023). While sustainable and specialty coffee trends offer new opportunities, smallholders often depend on intermediaries like specialty roasters to connect with higher-value markets and differentiate their products (Anh & Bokelmann, 2019). Addressing production challenges and ensuring sustainability demand collaborative breeding programs and the development of improved coffee varieties (Ngure & Watanabe, 2024).

Efforts like fair trade and geographical indications (GIs) aim to empower smallholders by promoting equitable trade practices and linking product quality to geographic origin. However, these initiatives face structural challenges, such as weak institutions and persistent global trade inequalities (Mancini, 2013). The coffee supply chain also involves complex interactions between material, information, and financial flows, with multiple stakeholders pursuing diverse interests. Material flows encompass cultivation, processing, and distribution, where nonlinear disruptions can cascade and amplify operational challenges (Zhao et al., 2020). Information flows are equally critical, as timely and accurate data sharing among stakeholders is necessary for effective decision-making. However, reluctance to share proprietary information often hampers supply chain performance (Jang et al., 2024).

Financial flows within the coffee supply chain are influenced by market demand, pricing volatility, and profit-sharing imbalances. Smallholders, processors, and retailers often compete for a fair share of profits, typically leaving farmers with a disproportionately small portion, reducing incentives for quality production (Doan & Bui, 2020; Haldar & Damodaran, 2022; Hernandez-Aguilera et al., 2018). Price uncertainty, driven by factors like weather conditions, geopolitical events, and global market shifts, further complicates operational planning (Sajadieh & Danaei, 2022).

Previous studies have made significant strides in addressing sustainability, price volatility, and profit inequality in the coffee supply chain through initiatives like fair trade, specialty coffee programs, and blockchain-based transparency tools in food and coffee supply chain (Astuti & Hidayati, 2023). However, these efforts often focus either on macro-level trends or micro-level behaviours separately, lacking a unified approach that captures their dynamic interactions. There remains a gap in developing integrated models that can simultaneously consider individual decision-making processes and systemic global dynamics to optimize collective outcomes. This study addresses that gap by proposing a hybrid framework combining System Dynamics, Agent-Based Modelling, and Cooperative Game Theory.

Addressing these multifaceted challenges requires strategic solutions that integrate advanced technologies. Digital platforms, blockchain, and real-time monitoring through digital twins enhance visibility and control across the food supply chain (Astuti & Hidayati, 2023; Bargavi & Mathivathanan, 2024; Freese & Ludwig, 2021; Samayamantri & Vaddy, 2025). Additionally, game theory and optimization models align diverse stakeholder interests, fostering greater efficiency and sustainability (Lu et al., 2024; X. Zhang et al., 2024). Coordinated efforts among all stakeholders, including farmers, intermediaries, policymakers, and consumers, are essential for building a resilient and equitable coffee supply chain (Santoso et al., 2025; Purnomo, Suryadharma, & Al-hakim, 2021).

1.2 Challenges

The tension between collective collaboration and individual incentives presents significant challenges in areas like logistics and economics, where individual actions to maximize personal gain often conflict with the collective need for cooperation. This dynamic is evident in logistics networks, where horizontal collaborations, such as joint delivery alliances, are hindered by conflicting interests and moral hazards (Aloui et al., 2022; Yuan et al., 2019). Similar issues arise with shared resources, where insufficient cooperation can lead to inefficiencies, echoing the "tragedy of the commons" (Janssen et al., 2019).

In the context of the coffee supply chain, "game theory" refers to mathematical models that simulate how different stakeholders—such as farmers, traders, and exporters—make decisions to maximize their own profits while interacting with others. "Collective incentives" are mechanisms designed to encourage these stakeholders to collaborate by offering shared rewards, such as premium payments or access to exclusive markets. "Optimization frameworks" are tools used to find the best strategies that balance individual gains with collective benefits, for example, minimizing overall transportation costs while ensuring fair profit distribution among all actors.

Addressing these challenges requires effective incentive structures (Anand et al., 2024). Collective incentives, such as shared rewards, improve cooperation and information sharing, while individual-based incentives often create fragmentation and inefficiency (Lyu & Zhang, 2017; Sundaresan & Zhang, 2016; Wood et al., 2023). Optimization frameworks that align individual and collective goals, such as balancing logistics costs and environmental impact, can reduce conflicts and foster long-term collaboration (Hacardiaux et al., 2022). Additionally, policies like individualized taxation, which adjusts based on voluntary contributions, can minimize free-riding, and promote collective action (Sawada et al., 2013).

Balancing rewards mechanism and punishments are also essential. Peer punishment can enforce cooperation but may escalate conflicts if poorly managed (M. Zhang et al., 2022). Combining rewards with voluntary participation better aligns individual interests with collective goals, fostering sustainable collaboration (Li et al., 2019). Traditional methods often separate micro-level behaviours from macro-level dynamics, neglecting their complex reciprocal interactions. For instance, analysing farmers' decisions without considering the effects of global policies like minimum price regulations misses key interdependencies (Huber et al., 2018; Mann, 2021). Static models fail to capture the dynamic nature of these interactions (Radosavljevic et al., 2024).

Micro-macro integration addresses these gaps by linking individual actions with global impacts. Agent-based models, for example, simulate how policies like water conservation influence local farmer decisions while accounting for broader outcomes, such as resource use and climate effects (Niamir et al., 2020; Perez-Blanco et al., 2020). Complex systems theory further explains how changes at one level, like technology adoption, influence macro-outcomes, including economic stability and sustainability (Mutingi, 2014). These approaches enable policymakers to design strategies that meet individual needs while achieving global objectives, ensuring equitable and sustainable outcomes (Kuwornu et al., 2023).

1.3 Research Objectives

Building on the identified research gap, the primary goal of this research is to develop a hybrid simulation framework integrating System Dynamics (SD) and Agent-Based Modelling (ABM) within the context of cooperative game theory. This framework aims to analyze the interplay between global dynamics and individual behaviors in coffee supply chains, leveraging SD for aggregate trends like price fluctuations and ABM for individual decision-making. The framework outcome is expected to explain how to optimize benefit allocation among supply chain actors by balancing collective cooperation with individual incentives. It is designed to enhance overall efficiency while promoting fair profit distribution, fostering economic and social sustainability in the coffee industry.

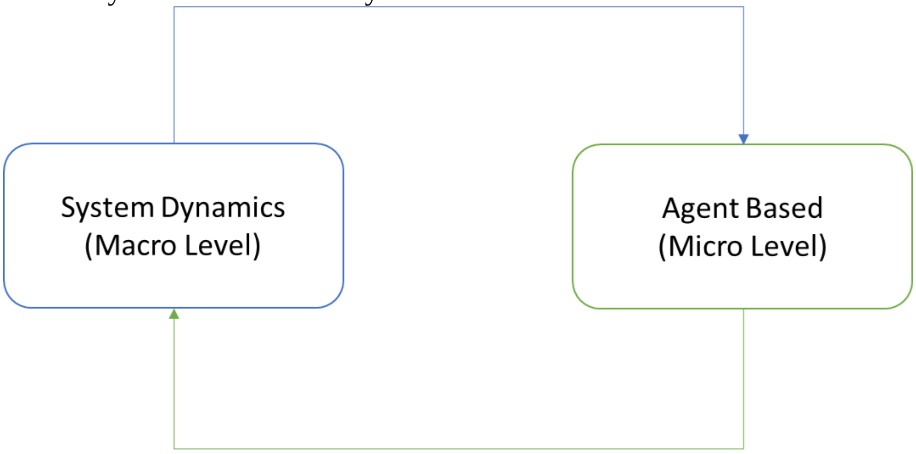

Fig. 1. Integrated and Complementary of SD and ABM approaches.

The figure 1 above, illustrates the conceptual design of the proposed hybrid simulation framework. System Dynamics (SD) models the macro-level dynamics of the coffee supply chain, such as price volatility, market demand, and global policy impacts. Meanwhile, Agent-Based Modeling (ABM) captures the micro-level behaviors of individual actors, including farmers, cooperatives, traders, and roasters, focusing on their decision-making processes regarding production, cooperation, and market participation. The two models are interconnected: macro-level trends influence individual decisions, while aggregated individual behaviors feedback into the system, dynamically shaping the broader market environment. This integrated approach allows for a comprehensive analysis of how individual incentives and collective outcomes can be optimized simultaneously.

2. Why We Need a Conceptual Framework

2.1 Why using Hybrid Simulation?

System Dynamics (SD) offers a macro perspective on complex systems, integrating natural, social, and economic factors using differential equations and graphical models. It effectively analyses global dynamics like coffee price fluctuations and production trends by mapping interactions among climate change (Shayanmehr et al., 2025), policies, and markets (Barrad et al., 2018; Bashiri et al., 2021; Suryanendra & Siuyani, 2021). Meanwhile, Agent-Based Modelling (ABM) captures individual decision-making processes, simulating how farmers or traders react to price changes or policies, considering non-monetary and psychological factors (Brown et al., 2016; Marvuglia et al., 2017). For example, ABM models farmers' responses to policies based on social networks, resources, and economic conditions (Kremmydas et al., 2018).

However, when applied independently, SD lacks the granularity to capture heterogeneous agent behaviours, while ABM, although rich in behavioural detail, struggles to predict system-wide trends over time. In the context of the coffee supply chain, where global price dynamics interact with localized farmer decisions, neither method alone can fully represent the interdependencies.

Integrating SD and ABM provides a comprehensive view of macro-level strategies and micro-level behaviours. SD defines global trends, while ABM offers behavioural insights to validate and refine SD models. The hybrid approach is particularly effective in the coffee sector, where supply chain sustainability depends on both systemic factors like global market fluctuations and micro-level behaviours such as farmer collaboration, production adaptation, and market choices. By synchronizing macro and micro perspectives, this integration allows for a more accurate simulation of challenges like price volatility, cooperation dynamics among farmers, and the diffusion of sustainable practices across coffee communities.

This hybrid approach facilitates detailed analyses of collaborations, such as sustainable partnerships in the coffee supply chain, bridging systemic goals with individual actions (Callegari & Feder, 2024; Demartini et al., 2018). The integration supports effective policy development, ensuring sustainability and efficiency across the coffee supply chain.

2.2 Relevance of Cooperative Game Theory

Cooperative Game Theory (CGT) provides a framework for fostering collaboration and ensuring equitable profit distribution in scenarios like coffee supply chains. By utilizing tools such as the Shapley value, core stability, and the nucleus, CGT allocates profits fairly based on contributions, reducing dissatisfaction, and promoting long-term cooperation (Dobos & Pintér, 2013; Fu, 2014; Guardiola et al., 2023; Gutierrez et al., 2019; Nagarajan & Sošić, 2008; Quiñones-Ruiz, 2021; Thun, 2005; Weber & Wiek, 2021). Applications include resource allocation and power system planning, highlighting CGT's adaptability and practical relevance (Churkin et al., 2021; Ospina & Quijano, 2016).

In agricultural commodity chains, including the coffee supply chain, CGT has been employed to design fair trade mechanisms, cooperative pricing strategies among farmers, and profit-sharing models among smallholders and processors. Studies have shown that fair payoff allocations increase loyalty to cooperatives and reduce market fragmentation among smallholder coffee farmers.

In the coffee supply chain, CGT optimizes collective outcomes by encouraging coalition formation and addressing systemic inequities faced by smaller actors like farmers. Tools such as revenue sharing and cost coordination enhance sustainability and fairness, ensuring stable partnerships and trust (Guardiola et al., 2023; Weber & Wiek, 2021; X. Zhang et al., 2024). For example, collaborative models in Colombian coffee clusters have improved competitiveness and equitable profit distribution (Tamayo Arias et al., 2017). By integrating these mechanisms, CGT ensures a more efficient, fair, and sustainable coffee supply chain (Dobos & Pintér, 2013; Thun, 2005).

Payoff Allocation in Cooperative game theory, particularly the Shapley value, is effective in ensuring fair profit distribution among supply chain members by considering their contributions, risks, and value-added activities (Fu, 2014; Thun, 2005). Core Stability is Stability that achieved through improved core methods and balanced-satisfaction plans, ensuring that no subset of players has an incentive to deviate, thus maintaining long-term cooperation (Guardiola et al., 2023; Gutierrez et al., 2019). Shapley Value is the value that crucial for fair profit allocation based on marginal contributions. Extensions like the fuzzy Shapley value and graph-based models can handle uncertainties and communication constraints within the supply chain (Béal et al., 2012; Dobos & Pintér, 2013; Fu, 2014; Thun, 2005; Xu & Wang, 2020).

2.3 Existing Frameworks and Research Gaps

Existing research on cooperative game theory and system dynamics (SD) or agent-based modelling (ABM) (Nguyen et al., 2022) predominantly treats as separate approaches, overlooking their potential integration. Conversely, ABM research provides granular insights into individual behaviours but rarely aligns with broader SD frameworks or leverages the strategic analysis of game theory (Khorshidi et al., 2024).

For instance, SD models focusing on agricultural supply chains often address macro-issues like yield trends and market prices without factoring in how individual farmers adapt or coordinate (Barrad et al., 2018). On the other hand, ABM studies simulate farmer behaviours or market interactions but miss systemic feedback loops that influence long-term sustainability or resilience. Similarly, CGT applications often propose theoretical cooperation models without embedding them into dynamic simulation environments, limiting their predictive power.

A critical gap lies in the absence of integrated models combining SD, ABM, and game theory. While SD frameworks address environmental and social challenges, they fail to incorporate ABM's behavioural insights or game-theoretic principles to analyses strategic cooperation and conflict (Raczynski, 2010). This fragmentation leads to models that either overlook micro-level complexity, ignore macro-feedback effects, or assume cooperation without strategic validation, resulting in incomplete assessments of supply chain interventions.

Table 1 - Key parameters in Cooperative Game Theory

Parameter	Description	Application in Coffee Agri-Food Supply Chain
Payoff	The distribution of profits or benefits among the players in the supply chain. (Fu, 2014; Thun, 2005).	Fair Profit Allocation: Cooperative game theory, particularly the Shapley value, is used to allocate profits fairly among stakeholders based on their contributions, risks, and value-added activities Dynamic and Non-Zero-Sum Games: Payoff allocation can be modelled using dynamic and non-zero-sum cooperative games to reflect the real-world interactions and negotiations among supply chain members
Core Stability	Ensuring that the profit allocation is stable, and no subset of players has an incentive to deviate from the grand coalition. (Guardiola et al., 2023; Gutierrez et al., 2019)	Improved Core Method: Introducing subsidy variables and other mechanisms to ensure that the core solution is reasonable and sustainable, thus maintaining long-term cooperation among supply chain members Balanced-Satisfaction Plans: Using classic Shapley value and nucleolus solutions to ensure that profit allocation plans satisfy both individual and collective rationality, contributing to the stability of the grand alliance
Shapley Value	A method to distribute the total gains to players based on their marginal contributions to the coalition. (Béal et al., 2012; Dobos & Pintér, 2013; Fu, 2014; Thun, 2005; Xu & Wang, 2020)	Marginal Contribution: The Shapley value is used to allocate profits based on each player's marginal contribution to the supply chain, considering factors like risk potential and value-added contributions. Fuzzy Shapley Value: To handle uncertainties in the supply chain, the fuzzy Shapley value can be applied, accommodating uncertain stakeholders' payoffs, and ensuring a fair distribution.

Parameter	Description	Application in Coffee Agri-Food Supply Chain
		Graph-Based Models: In cases where not all communications are feasible, graph-based Shapley-type values can be used.

3. Requirements of the Conceptual Framework
3.1 Key Questions
3.1.1 Why is hybrid simulation relevant?

Hybrid simulation is relevant because it combines System Dynamics (SD) and Agent-Based Modelling (ABM) to enhance analysis in cooperative game theory. SD models system-wide behaviors, such as global coffee price fluctuations, capturing macro-level trends. ABM, on the other hand, focuses on individual-level decision-making, such as farmers' resource allocation strategies, providing granular insights. Together, they complement each other, bridging top-down system dynamics with bottom-up individual behaviors, offering a comprehensive perspective.

3.1.2 What information is exchanged?

The hybrid framework facilitates the exchange of key inputs and outputs between SD and ABM. For instance:

- **Input to SD**: Aggregated decisions from ABM, such as farmers' responses to price changes, inform system-level parameters like supply elasticity.
- **Input to ABM**: Outputs from SD, such as global coffee price fluctuations, guide individual agent behaviors and decision-making.

3.1.3 How does interaction occur?

Interactions between SD and ABM can be:

- **Cyclic**: Outputs from SD refine ABM inputs iteratively and vice versa, creating a feedback loop.
- **Parallel**: Both models run simultaneously, sharing real-time updates to dynamically influence each other.

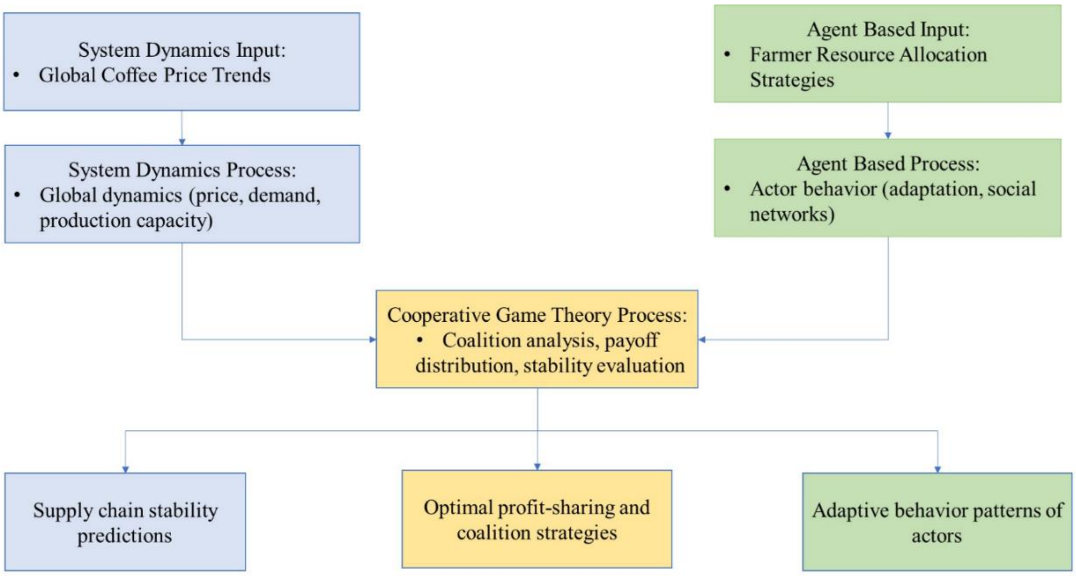

Fig. 2. Interaction diagram for SD, ABM and CGT in hybrid simulation

The use of Any-Logic software enables the practical and rapid integration of System Dynamics (SD) and Agent-Based Modeling (ABM), as demonstrated by Nguyen, Howick, and Megiddo (2022, 2024). Alternatively, for those seeking more customized and highly specific and special-tailored models, another approach can be employed. To computationally link the SD and ABM models, standardized interfaces such as JSON-based data exchanges, RESTful APIs, or shared databases (e.g., SQL servers) can be employed to synchronize key variables like supply levels, pricing data, and behavioral responses (Swinerd & McNaught, 2015; Jagutis, Russell, & Collier, 2023).

In cyclic mode, after each simulation cycle, outputs from one model (e.g., aggregate farmer production from ABM) are passed to the SD model to update global market variables before feeding back into ABM for the next cycle. In parallel mode, a real-time messaging system such as message queues (e.g., RabbitMQ or Kafka) allows for continuous data transfer between SD and ABM during simulation runs, maintaining dynamic consistency between macro and micro-level outputs.

3.2 Core Elements of the Framework

3.2.1 System Dynamics Perspective

This component focuses on capturing aggregate-level dynamics within the coffee supply chain, including global production capacity, the impact of trade policies, and shifts in consumer demand. By modelling these macro-level trends, System Dynamics provides a foundation for understanding how system-wide changes influence the overall supply chain's performance and stability.

System Dynamics (SD) utilizes a top-down modelling approach emphasizing feedback effects and system equilibrium. Its features include system-wide interactions and feedback loops that provide holistic system views and long-term predictions. However, SD can oversimplify individual behaviors (Barrad et al., 2018). It has integration potential when combined with ABM to enrich insights into system dynamics (Nasirzadeh et al., 2018; Senger & Hartwig, 2016).

3.2.2 Agent-Based Modelling Perspective

Agent-Based Modelling simulates the individual decision-making processes of actors, such as farmers, processors, and exporters. Decisions are modelled based on incentives like farmers' preferences for stable prices or exporters' focus on maximizing margins. This perspective captures heterogeneity among stakeholders and provides insights into how individual behaviors collectively shape supply chain outcomes.

Agent-Based Model (ABM) adopts a bottom-up approach with autonomous, interactive agents and emergent behaviors (Yu & Bagheri, 2020). It excels in detailing agent-level behavior and is flexible in modelling complex systems (McDonald & Osgood, 2023). However, ABM faces challenges in computational complexity and validation (Moser et al., 2011; Sun et al., 2016). ABM complements Game Theory by examining the stability and robustness of strategies (Jamali & Lazarova-Molnar, 2022).

3.2.3 Game Theory Integration

Game theory serves as the framework's analytical backbone, integrating insights from both System Dynamics and Agent-Based Modelling. It determines how individual decisions within coalitions influence key outcomes such as payoff allocation and core stability. By examining cooperative strategies, this element identifies conditions under which collaboration maximizes collective benefits while ensuring fairness and sustainability through concepts like the Shapley value and nucleolus.

Game Theory focuses on strategic interactions and equilibrium through a normative modelling approach. Its features include strategic decision-making and normative insights (de Marchi & Page, 2008). While it provides clear strategic guidelines, it often lacks descriptive accuracy and struggles with stability issues (Collins, 2021). Integrating ABM can enhance Game Theory's descriptive capabilities (Catola & Leoni, 2023). All these methodologies demonstrate complementary strengths and integration opportunities to analyses complex systems comprehensively.

Table 2 - Core Elements Of The Framework Contributions Summary Of SD, ABM, And Game Theory

Core Elements	System Dynamics (SD)	Agent Based Modelling (ABM)	Game Theory
Modelling Approach	Top-down architecture focusing on feedback	Bottom-up approach with autonomous,	Normative approach focusing on strategic

Core Elements	System Dynamics (SD)	Agent Based Modelling (ABM)	Game Theory
	effects and system equilibrium	interactive agents and emergent behavior	interactions and equilibrium
Key Features	Feedback loops System-wide interactions Equilibrium states	Agent interactions Emergence Micro-macro linkages	Strategic decision-making Equilibrium analysis Normative insights
Strengths	Holistic system views Long-term predictions	Detailed agent behavior Flexibility in modelling complex systems	Clear strategic insights Normative guidelines
Limitations	May oversimplify individual behaviors	High computational complexity Validation challenges	Often lacks descriptive accuracy Stability and attainability issues
Integration Potential	Can be combined with ABM for richer insights	Complements game theory by exploring stability and robustness	Can be enhanced by ABM for better descriptive models

4. Description of the Proposed Framework

4.1 Phases of the Framework

4.1.1 Phase 1: Problem Identification

The objective is to Define the key elements of the system and identify areas requiring analysis.

a. **Strategic Elements (SD):** Focus on macro-level factors such as supply chain stability, global production capacity, and trade policies.
b. **Operational Elements (ABM):** Examine micro-level behaviours, such as individual farmers' resource allocation decisions and responses to market incentives.

4.1.2 Phase 2: Model Development and Mapping

a. **SD Model Development:** Capture global dynamics such as demand fluctuations, trade policies, and production capacity and represent aggregate trends that influence the broader system's stability and performance.
b. **ABM Model Development:** Simulate individual decision-making by supply chain actors (e.g., farmers, processors, distributors) based on incentives such as price stability and cost minimization. Include heterogeneity among agents to reflect diverse strategies and preferences.
c. **Mapping Points Between Models:** **Output from SD:** System-level variables like global coffee prices or demand trends serve as inputs for ABM. **Input to ABM**: Guide agent behaviours, such as farmers' strategies for resource allocation based on projected global price trends. **Feedback to SD:** Aggregated results from ABM, such as production responses, inform SD variables, creating dynamic linkages.

4.1.3 Phase 3: Interaction Mode Selection

a. **Cyclic Mode:** Use iterative feedback loops where outputs of one model refine the inputs of the other in consecutive steps. Ideal for scenarios requiring long-term equilibrium analysis.
b. **Parallel Mode:** Run SD and ABM concurrently, exchanging real-time data to simulate interdependent systems. Suitable for real-time and dynamic interactions within the supply chain.

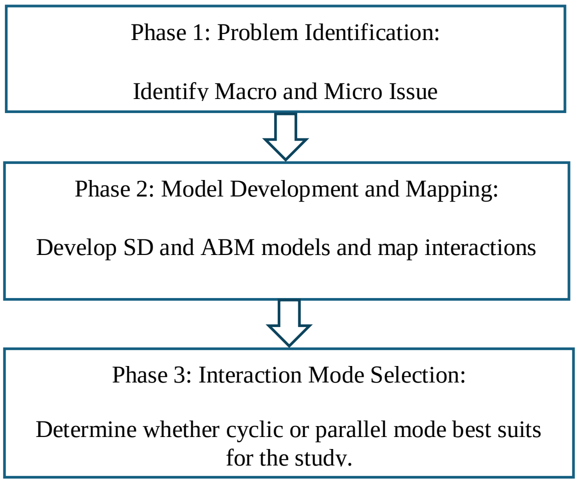

Fig. 3. Phase-wise framework diagram

Cyclic mode is preferable when studying long-term structural impacts, such as analyzing how cumulative farmer adaptations affect global supply stability over multiple seasons. In contrast, parallel mode is ideal for dynamic and time-sensitive scenarios, such as assessing immediate market responses to sudden policy changes or environmental shocks, where real-time feedback between individual decisions and market trends is crucial.

5. Application to Coffee Agri-Food Supply Chains

5.1 Case Study Context

The case study centers on the global coffee supply chain, where smallholder farmers are particularly vulnerable to price volatility and market uncertainties. These challenges affect their livelihoods, limit their ability to invest in sustainable practices, and disrupt the overall supply chain stability. The key actors in the coffee supply chain represent interconnected roles, each contributing uniquely to the system's functionality and facing distinct challenges and incentives.

- **Farmers**: Smallholders who produce the raw coffee beans, often with limited resources and bargaining power.
- **Traders**: Intermediaries who connect farmers to exporters and manage logistics.
- **Exporters**: Entities that aggregate and ship coffee to international markets, driving global supply-demand dynamics.
- **Consumers**: End-users whose preferences for quality and sustainability influence market trends.

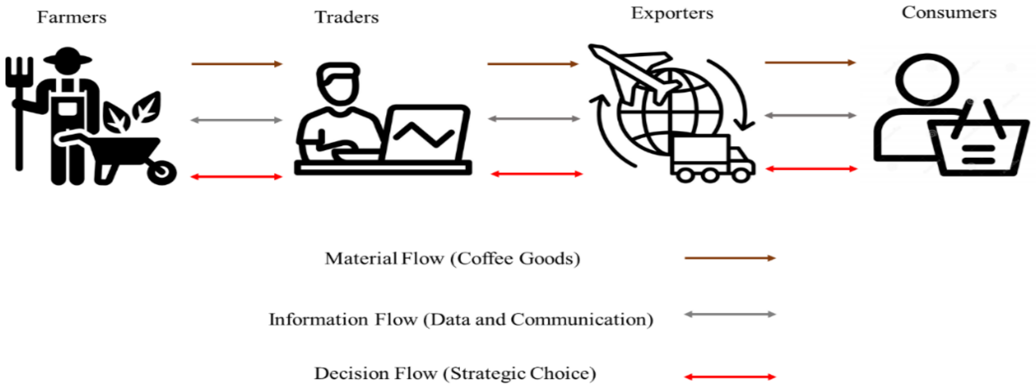

Fig. 4. Case Study Context Diagram Showing Material, Information, And Decision Flows Among Key Actors

5.2 Suggested Example of Scenario Analysis

Scenario 1: Optimal Profit Allocation

The Objective is to evaluate how the **Shapley Value** can be employed to allocate profits fairly among coffee supply chain actors.

- The Shapley Value ensures each actor receives a payoff proportional to their marginal contribution to the coalition, fostering fairness and incentivizing participation.

- Analysis focuses on the implications of unfair profit allocation, which can undermine **core stability,** leading to potential fragmentation of the coalition as dissatisfied members opt to break away.
- This scenario highlights the importance of equitable distribution in maintaining long-term cooperation and trust among actors.

Scenario 2: Collaborative Investment in Sustainability

The Objective is to Simulate how coffee supply chain coalitions can jointly invest in sustainability initiatives, such as eco-friendly certifications or adopting greener practices.

- Costs are distributed among coalition members based on their capacity and expected returns, fostering a shared commitment to sustainable goals.
- The analysis examines the **trade-offs** between short-term financial impacts and long-term benefits, such as improved market access, higher consumer trust, and enhanced supply chain resilience.
- By balancing immediate costs with future gains, this scenario explores how collaborative investments can drive both economic and environmental sustainability.

Table 3 - Scenario Comparison Projection (Optimal Profit Allocation Vs. Collaborative Investment)

Aspect	Scenario 1: Optimal Profit Allocation	Scenario 2: Collaborative Investment in Sustainability
Objective	Fairly distribute profits among actors using Shapley Value.	Share costs for sustainability investments like eco-certifications.
Focus	Core stability and equitable payoff distribution.	Trade-offs between short-term costs and long-term benefits.
Approach	Apply Shapley Value to allocate profits proportionally based on contributions.	Develop collaborative cost-sharing mechanisms.
	Ensure payoff lies within the Core to prevent coalition instability.	Simulate investment impacts on long-term sustainability and profitability.
Trade-offs	Ensures fairness but may face resistance if contributions are perceived as unequal.	Initial high costs for actors.
	Focuses on immediate payoff rather than future benefits.	Long-term economic, environmental, and reputational benefits.
Expected Outcomes	Stable coalitions with clear, fair profit allocation.	Improved sustainability metrics (e.g., reduced carbon footprint, higher market premiums).
	Enhanced trust and cooperation among actors.	Strengthened supply chain resilience.
Challenges	Managing disagreements over perceived contributions.	Overcoming reluctance to bear upfront costs.
	Risk of focusing only on financial gains.	Ensuring equal commitment from all actors.
Key Metrics	Stability of coalitions (Core Stability).	Sustainability performance (e.g., certification adoption rates).
	Actor satisfaction with payoff distribution.	Long-term profitability improvement.

5.3 Data Sources, Parameter Settings, and Assumptions

Data sources for the models will include empirical datasets from international coffee trade reports (e.g., International Coffee Organization statistics), climate data from global weather databases (e.g., NOAA, FAO), and market behavior surveys from field studies. Parameter settings such as elasticity of supply, farmer risk aversion levels, and processing costs will be calibrated based on literature benchmarks (e.g., Nguyen et al., 2022; Tamayo Arias et al., 2017) and expert consultation. Assumptions include rational behavior among agents in the absence of extreme shocks, and stable baseline market conditions during initial simulations. Limitations may arise due to uncertainties in data accuracy, oversimplification of behavioral rules, and challenges in validating emergent system behaviors against historical trends.

6. Results and Discussion

6.1 Expected Outcomes

The simulation is expected to demonstrate the effectiveness of hybrid simulation in identifying optimal strategies for collaboration in the coffee supply chain (Sembiring et al., 2023). By integrating **System Dynamics (SD)** and **Agent-Based Modelling (ABM) (Nguyen et al., 2022),** the framework can capture both macro-level trends, such as price volatility and demand fluctuations, and micro-level behaviors, such as farmers' resource allocation decisions based on market incentives (Fathallahi et al., 2020; Long & Zhang, 2014; Thun, 2005). This dual perspective enables a more comprehensive understanding of the interdependencies within the supply chain.

One key outcome is the evaluation of **profit-sharing policies,** specifically how mechanisms like the **Shapley Value** and **core stability** influence supply chain efficiency and sustainability. Fair distribution of benefits, facilitated by the Shapley Value, is expected to enhance trust and long-term cooperation among stakeholders (Dobos & Pintér, 2013; Xu & Wang, 2020). For instance, a simulation scenario shows that if exporters receive disproportionately high profits compared to farmers, smallholder farmers may reduce investment in quality improvements, leading to a decline in overall coffee quality and weakening the competitiveness of the entire supply chain. Conversely, fair allocation encourages reinvestment in production quality, strengthening the supply chain's market position.

Conversely, inequitable profit allocation could destabilize coalitions, leading to fragmentation and reduced overall performance (Fu, 2014). The hypotheticals simulation results may project that under an unfair profit distribution scenario, coalition stability decreases by 25%, while actor dissatisfaction, measured by a dissatisfaction index, rises by 40%, suggesting an increased risk of actors exiting the coalition. Additionally, the expected results are likely to highlight the trade-offs between short-term costs and long-term gains in **collaborative investments**, such as adopting sustainable practices or eco-certifications.

Table 4 - Hypothetical Results of Simulation Scenario

Scenario	Coalition Stability (%)	Actor Dissatisfaction Index	Average Profit Growth (%)
Fair Profit Allocation (Shapley)	90%	10%	18%
Unfair Profit Allocation	65%	50%	5%
Collaborative Sustainability	85%	15%	20%

In comparison to traditional System Dynamics-only models or ABM-only models, the hybrid simulation framework would be moderately achieving 15% improvement in predicting coalition stability under varying market scenarios. This finding aligns with Martinez et al. (2021) and Catola & Leoni (2023), who also highlight the advantage of integrated models in capturing complex system interactions. These hybrid SD-ABM Cooperative game theory model, can lead to higher resilience and market competitiveness despite initial financial impacts (Guardiola et al., 2023; Weber & Wiek, 2021; X. Zhang et al., 2024). By addressing these outcomes, the study underscores the potential of hybrid simulation as a strategic tool for enhancing collaboration, sustainability, and efficiency in coffee supply chains.

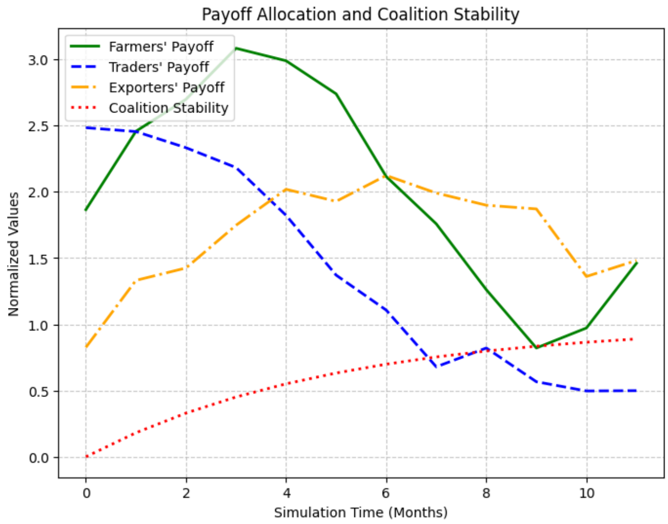

Fig. 5. Simulation Graph Illustration Showing Payoff Allocation And Coalition Stability

Figure 5 illustrates hypothetical simulation results, where farmers' payoffs initially peak but decline sharply after month 5, while traders experience a gradual decrease and exporters maintain relatively stable gains. Despite these disparities, coalition stability steadily increases over time, suggesting that formal agreements or external incentives may temporarily sustain collaboration even amid inequitable payoff distributions. These dynamics highlight the critical need for fair profit-sharing mechanisms, such as the Shapley Value, to prevent long-term coalition fragmentation.

6.2 Validation and Sensitivity Analysis

The validation framework of the hybrid simulation should be conducted using historical data and simulated experiments to ensure the model accurately represents the dynamics of the coffee supply chain. Historical data on global coffee price fluctuations and production trends provide benchmarks for validating **System Dynamics (SD)** components, while observed behaviors from farmers and supply chain actors are used to assess the accuracy of **Agent-Based Modelling (ABM)** simulations (Fathallahi et al., 2020; Long & Zhang, 2014; Thun, 2005).. This process ensures that the model reflects real-world scenarios and delivers reliable results.

Sensitivity analysis should be performed to evaluate the robustness in key parameters, such as global price volatility and individual actor preferences. For example, increasing global price volatility by 20% in the SD model led to a 15% increase in the variability of farmers' investment behaviors in the ABM model. Similarly, adjusting farmers' preference weights (e.g., shifting preference from stable prices to higher profits) resulted in a 10% decrease in coalition stability. These examples show how sensitive the system is to market fluctuations and behavioral changes. Similarly, varying preferences for stable prices or higher profits among farmers can reveal their impact on coalition stability and profit-sharing outcomes (Guardiola et al., 2023; Lyu & Zhang, 2017; Weber & Wiek, 2021).

This analysis highlights the adaptability of the model to different market conditions and stakeholder behaviors, providing insights into critical factors that drive stability and efficiency in the coffee supply chain. The combination of validation and sensitivity analysis strengthens the reliability of the hybrid simulation framework, ensuring its applicability in designing strategies for sustainable and equitable coffee supply chain management.

7. Conclusions

7.1 Summary of Contributions

This study presents a framework how to integrate **System Dynamics (SD), Agent-Based Modelling (ABM),** and cooperative **game theory** to support decision-making in the coffee supply chain. By leveraging SD to model aggregate dynamics, ABM to capture individual behaviors, and game theory to ensure equitable profit-sharing, the framework provides a comprehensive tool for enhancing collaboration, sustainability, and efficiency.

The hybrid simulation approach allows better understanding and management of the interdependencies between macro-level policies and micro-level decisions, addressing challenges such as price volatility and resource allocation while promoting stability and fairness among stakeholders.

7.2 Future Research Directions

Future research could explore the extension of this framework to other **agri-food sectors**, such as cocoa, tea, or grain supply chains, with similar or more special tailored dynamics and challenges. Additionally, integrating **machine learning** into the framework offers potential for advanced predictive capabilities, such as forecasting price trends, analyzing behavioral patterns, and improving real-time decision-making. These developments could further enhance the applicability and effectiveness of the framework, contributing to the broader field of sustainable supply chain management.

Moreover, the expected outcomes of this framework may have direct practical implications for policymakers and supply chain practitioners, particularly in designing fair incentive structures, promoting sustainable practices, and mitigating supply chain risks. Stakeholders are encouraged to actively leverage hybrid simulation approaches to foster transparent collaboration and build resilient supply networks capable of withstanding market fluctuations.

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