Management Strategies and Engineering Sciences 2027; 9(2):1-18

Estimating the Reliability Model of Supply Centers in Green Value Chain Management of Manufacturing Industries Using the System Dynamics Approach

Arash Rafati [1], Hassan Mehrmanesh[1*] Hossein Moinzad[1]

[1] Department of Management, CT.C., Islamic Azad University, Tehran, Iran

*** Corresponding author email address**: ha.mehrmanesh@iau.ac.ir

Received: 2026-02-01 **Reviewed:** 2026-05-20 **Revised:** 2026-05-27 **Accepted:** 2026-06-03 **Published:** 2027-03-01

Abstract

The present study was conducted with the aim of estimating a reliability model for supply centers in the green value chain management of manufacturing industries using the system dynamics approach. In terms of purpose, this research is applied, and in terms of nature, it is a descriptive–analytical study. Initially, through a systematic review of the literature, document analysis, and expert consultation, the variables influencing the reliability of the green value chain were identified. Subsequently, the Fuzzy Delphi technique was employed to screen the identified indicators. The results of this stage revealed that ten components—environmental sustainability, operational efficiency, social and ethical responsibility, green innovation management, traceability and transparency, environmental risk management, culture-building and training, policymaking and regulatory compliance, utilization of advanced technologies, and the economic viability of green activities—obtained crisp values above the acceptance threshold and were therefore retained in the final model. Based on these components, the conceptual research model was developed using causal loop diagrams and subsequently transformed into a stock-and-flow model, which was simulated in the Vensim software environment. The modeling results demonstrated that interactions among variables, through reinforcing and balancing feedback loops, shape the dynamic behavior of green value chain reliability. Among these, the "green innovation and sustainability," "policymaking and environmental risk," "training, culture, and responsibility," "economic viability and technology adoption," and "transparency and supply chain reliability" loops were identified as the most influential feedback structures. Scenario analysis further indicated that strengthening environmental risk management, promoting green innovation, increasing the adoption of advanced technologies, improving transparency, and enhancing organizational culture can contribute to improved environmental sustainability, increased operational efficiency, and greater economic viability of green activities. Moreover, the structural validity of the model was examined and confirmed through boundary adequacy tests, structure assessment, extreme-condition tests, integration error analysis, behavior reproduction tests, and sensitivity analysis. Overall, the findings indicate that the reliability of supply centers within the green value chain is a multidimensional and dynamic phenomenon whose enhancement requires a systemic perspective, coordination among technological, economic, environmental, social, and institutional dimensions, and the implementation of integrated managerial policies.

Keywords: *Supply Center Reliability; Green Value Chain Management; Manufacturing Industries; Green Innovation; Environmental Sustainability.*

How to cite this article:

Rafati, A., Mehrmanesh, H., & Moinzad, H. (2027). Estimating the Reliability Model of Supply Centers in Green Value Chain Management of Manufacturing Industries Using the System Dynamics Approach. Management Strategies and Engineering Sciences, 9(2), 1-18.

1. Introduction

In today's highly competitive and environmentally conscious business environment, manufacturing industries are increasingly required to balance economic performance with environmental responsibility. Global concerns regarding climate change, resource depletion, environmental degradation, and increasing regulatory pressures have significantly transformed the operational priorities of organizations. As a result, traditional supply chain management approaches, which primarily focused on cost reduction and efficiency improvement, have gradually evolved toward more sustainable and environmentally responsible frameworks. Green Supply Chain Management (GSCM) has emerged as one of the most important strategic approaches for achieving sustainable development while maintaining organizational competitiveness. The fundamental objective of green supply chain management is to integrate environmental considerations into all stages of supply chain activities, including product design, material sourcing, manufacturing, distribution, consumption, and end-of-life management [1-3]. Recent studies indicate that organizations implementing green supply chain practices not only improve environmental performance but also enhance operational effectiveness, innovation capabilities, and long-term competitive advantage [1, 4, 5].

The increasing complexity of global supply networks has amplified the importance of supply center reliability as a critical determinant of supply chain performance. Supply centers constitute the foundational nodes of manufacturing supply networks because they are responsible for providing materials, components, information, and resources required for production activities. Any disruption, inefficiency, or unreliability within these centers can negatively affect the entire value chain and undermine organizational sustainability efforts. Consequently, supply center reliability has become a strategic concern for managers seeking to develop resilient and sustainable supply chain systems. Reliability in this context refers not only to the consistent delivery of products and services but also to the ability of supply centers to maintain environmental, economic, and social performance standards under changing conditions and uncertainties [6-8]. The reliability of supply centers becomes even more critical in green value chains because environmental objectives often introduce additional complexities, constraints, and performance requirements that must be managed simultaneously.

The concept of the green value chain extends beyond traditional supply chain management by emphasizing value creation through environmentally sustainable activities across the entire network of stakeholders. Green value chains seek to reduce environmental impacts while maximizing resource efficiency, promoting circular economy principles, and enhancing social responsibility. Within this framework, supply centers play a central role because their decisions directly influence resource consumption, waste generation, carbon emissions, and overall environmental performance. Therefore, improving the reliability of supply centers is essential for achieving the strategic objectives of green value chain management. Previous studies have demonstrated that environmental sustainability, operational efficiency, technological innovation, and stakeholder collaboration are among the key factors contributing to successful green supply chain implementation [2, 4, 9]. Furthermore, the effective integration of green practices throughout supply networks can enhance organizational adaptability and strengthen sustainable competitive advantage [1, 10, 11].

A growing body of literature has investigated the determinants and outcomes of green supply chain management across various industries. Research has highlighted the importance of environmental management systems, green procurement, eco-design, reverse logistics, and sustainable supplier relationships in improving environmental and economic performance [12-14]. Studies have also emphasized the role of supply chain agility and flexibility in responding to environmental challenges and market uncertainties. Agile supply chains are better equipped to adapt to changing customer demands, regulatory requirements, and environmental conditions, thereby enhancing organizational competitiveness and resilience [15, 16]. Nevertheless, despite substantial advances in the field, there remains limited understanding of how multiple organizational, technological, environmental, and institutional factors interact dynamically to influence the reliability of supply centers within green value chains.

One of the most significant developments in green supply chain research is the increasing recognition of technological innovation as a catalyst for sustainability transformation. Advanced technologies such as blockchain, artificial intelligence, big data analytics, Internet of Things (IoT), digital twins, and Industry 4.0 applications have fundamentally altered the way supply chains operate and are managed. These technologies facilitate real-time monitoring, traceability, transparency, predictive analytics, and risk management, all of which contribute to greater reliability and sustainability across supply networks [17-19]. Blockchain technology, for example, has been recognized as an effective tool for improving transparency, trust, and traceability in supply chains while reducing information asymmetry and operational risks [17, 18]. Similarly, Industry 4.0 technologies have been shown to enhance supply chain performance by increasing operational efficiency, reducing waste, and enabling more sustainable production systems [4, 19].

Environmental risk management represents another critical dimension influencing the reliability of supply centers in green value chains. Manufacturing industries are increasingly exposed to environmental uncertainties arising from climate change, resource scarcity, regulatory changes, and stakeholder pressures. Effective risk management strategies are therefore necessary to identify, assess, and mitigate environmental risks that may disrupt supply chain operations. Sustainable and closed-loop supply chain models have been developed to address these challenges by incorporating risk assessment mechanisms, reverse logistics systems, and environmental performance considerations into decision-making processes [8, 20, 21]. Moreover, uncertainty management has emerged as a crucial capability for achieving sustainability outcomes in circular and green supply chains, particularly in complex and rapidly changing environments [7].

In addition to technological and environmental factors, organizational capabilities and social dimensions play a fundamental role in determining the effectiveness of green supply chain initiatives. The resource-based view and dynamic capability perspectives suggest that sustainable competitive advantage can be achieved through the development of unique organizational capabilities, knowledge assets, innovation competencies, and learning cultures [22-24]. Green innovation management has been identified as a key mechanism through which organizations transform environmental challenges into opportunities for value creation and competitive differentiation [1, 2]. Furthermore, marketing capabilities, innovation ambidexterity, and strategic positioning have been found to enhance organizational performance and competitiveness by facilitating the successful implementation of sustainability-oriented strategies [10, 25, 26].

Social responsibility and ethical considerations have also become increasingly important in contemporary supply chain management. Stakeholders, including customers, investors, governments, and civil society organizations, expect companies to demonstrate responsible environmental and social behavior throughout their supply networks. As a result, organizations are increasingly investing in sustainability reporting, ethical sourcing practices, employee training programs, and stakeholder engagement initiatives to strengthen trust and legitimacy. These activities contribute to the development of transparent and reliable supply chains while enhancing organizational reputation and long-term performance [11, 22]. In particular, culture-building and training initiatives can foster environmental awareness and encourage employees to adopt behaviors that support sustainability objectives and operational excellence.

Policymaking and regulatory compliance constitute another important factor affecting green supply chain performance. Governments worldwide have introduced stricter environmental regulations, sustainability standards, and reporting requirements to promote responsible business practices. Compliance with these regulations often requires organizations to redesign processes, invest in cleaner technologies, and strengthen monitoring systems. While compliance may initially increase operational costs, it can also generate long-term benefits by reducing environmental risks, enhancing transparency, and improving organizational legitimacy [5, 6]. Research has shown that effective policy frameworks can facilitate the adoption of green practices and accelerate sustainability transitions across industries [3, 4].

Despite the growing body of knowledge on green supply chain management, existing studies have largely focused on isolated factors or static relationships among variables. Many investigations have employed optimization techniques, mathematical programming approaches, and conceptual frameworks to examine specific aspects of sustainable supply chains, including supplier selection, reverse logistics, risk assessment, and network design [8, 12, 14]. Although these studies provide valuable insights, they often fail to capture the dynamic interactions, feedback mechanisms, and nonlinear relationships that characterize real-world supply systems. Green value chains operate as complex adaptive systems in which technological, environmental, social, economic, and institutional factors continuously influence one another over time. Consequently, there is a need for analytical approaches capable of modeling such complexity and revealing the long-term behavioral patterns of these systems.

System Dynamics has emerged as a powerful methodology for understanding complex systems characterized by feedback loops, delays, accumulations, and nonlinear interactions. Unlike traditional analytical methods, System Dynamics enables researchers to investigate how system structures generate behavior over time and to evaluate the potential consequences of alternative policies and strategies. Previous studies have successfully applied System Dynamics to various supply chain management problems, including agility assessment, leagility evaluation, sustainability analysis, and operational performance improvement [27-29]. By integrating qualitative and quantitative information, System Dynamics provides a holistic perspective that facilitates the identification of leverage points and supports strategic decision-making in complex environments.

Given the strategic importance of supply center reliability in achieving sustainable value creation, the increasing complexity of green supply chains, and the limitations of existing static approaches, there is a clear need to develop a comprehensive dynamic model capable of capturing the multidimensional nature of this phenomenon. Such a model should incorporate environmental sustainability, operational efficiency, social and ethical responsibility, green innovation management, traceability and transparency, environmental risk management, culture-building and training, policymaking and regulatory compliance, advanced technology utilization, and the economic viability of green activities. Understanding the interactions among these factors can provide valuable insights for managers, policymakers, and researchers seeking to improve the reliability and sustainability of manufacturing supply networks.

Therefore, the aim of this study is to estimate a reliability model of supply centers in green value chain management within manufacturing industries using the System Dynamics approach.

2. Methodology

This study was conducted as an applied research project with a descriptive–analytical design aimed at estimating the reliability model of supply centers in the green value chain management of manufacturing industries through a system dynamics approach. System dynamics, originally developed by Forrester, was adopted as the principal methodological framework because of its capability to model complex, nonlinear systems characterized by feedback structures, delays, and dynamic interactions among variables. The approach facilitates a comprehensive understanding of how system behavior evolves over time as a result of interactions among its underlying structural components and decision-making processes. Unlike conventional analytical methods that primarily rely on quantitative datasets, system dynamics integrates subjective knowledge, documentary evidence, and numerical data, thereby enabling the representation of complex organizational and industrial phenomena in a holistic manner.

The research process began with an extensive review of the literature related to green value chain management, supply chain reliability, environmental sustainability, green innovation, operational efficiency, and related managerial concepts. In addition, project reports, organizational documents, and relevant industrial records were examined to identify key variables affecting the reliability of supply centers within green value chains. To enhance the validity of the conceptual framework, expert opinions were collected from a panel of academic specialists and professionals with expertise in supply chain management, sustainability, industrial engineering, and system dynamics. The preliminary conceptual model was developed in the form of causal loop diagrams representing the relationships among the identified variables. The resulting model was subsequently reviewed and validated by the expert panel before being transformed into a stock-and-flow structure suitable for dynamic simulation.

The study employed the Vensim software package as the primary modeling and simulation platform. Vensim was selected because of its extensive capabilities for developing causal loop diagrams, stock-and-flow models, mathematical formulations, and simulation scenarios. The software enables researchers to convert conceptual maps into executable dynamic models, automatically generate equations corresponding to system structures, and evaluate system behavior under different policy interventions and environmental conditions. Through this approach, the study sought to capture the dynamic interactions influencing supply center reliability and to examine the long-term consequences of alternative managerial and policy decisions within green value chains.

Data collection in this study relied on multiple complementary sources consistent with the principles of system dynamics modeling. The first source consisted of a comprehensive literature review, including scientific articles, books, industry reports, policy documents, and previous empirical studies addressing green supply chains, sustainable manufacturing, environmental management, organizational reliability, and green innovation. This review provided the theoretical foundation for identifying the major variables, causal relationships, and feedback mechanisms relevant to the reliability of supply centers in green value chains.

The second source of data involved documentary analysis. Various project documents, organizational reports, environmental assessments, and operational records related to manufacturing industries were examined to identify practical factors influencing reliability performance. Documentary evidence enabled the researchers to supplement theoretical findings with contextual information derived from real-world industrial settings and to establish more realistic relationships among model variables.

The third source consisted of expert knowledge and judgment. Expert opinions were incorporated throughout the model development process to validate causal relationships, identify missing variables, refine feedback structures, and evaluate the plausibility of simulation assumptions. To systematically screen and prioritize the identified indicators, the Fuzzy Delphi technique was employed. This method enabled the aggregation of expert judgments while accounting for uncertainty and ambiguity in qualitative assessments. Indicators that achieved acceptable crisp values above the predetermined threshold were retained in the final conceptual model. Through this process, the study identified and validated key dimensions, including environmental sustainability, operational efficiency, social and ethical responsibility, green innovation management, traceability and transparency, environmental risk management, culture-building and training, policymaking and regulatory compliance, utilization of advanced technologies, and the economic viability of green initiatives.

Within the system dynamics framework, causal loop diagrams served as an important modeling tool for representing cause-and-effect relationships among variables. Positive causal links indicated that changes in one variable produced changes in another variable in the same direction, whereas negative causal links reflected inverse relationships between variables. These causal structures were subsequently transformed into stock-and-flow models. The stock-and-flow representation consisted of stocks (state variables), flows (rates of change), converters (auxiliary variables and parameters), and connectors (information links). Stocks represented accumulations within the system, flows represented increases or decreases in stock levels over time, converters determined the operational behavior of system processes, and connectors illustrated the direction and influence of relationships among variables.

Data analysis was performed using the system dynamics methodology and the Vensim simulation environment. Following the identification and validation of key variables, causal loop diagrams were developed to illustrate the feedback structures governing the reliability of supply centers within green value chains. These diagrams enabled the identification of reinforcing and balancing feedback loops that shape system behavior over time. The validated causal structure was then translated into a stock-and-flow model to facilitate quantitative simulation and dynamic analysis.

Mathematical equations describing the relationships among variables were formulated based on theoretical foundations, documentary evidence, expert knowledge, and system dynamics principles. The stock-and-flow structure was constructed according to the fundamental system dynamics formulation, whereby the value of each stock variable is determined by its initial condition and the cumulative difference between inflows and outflows over time. This modeling approach allowed the simulation of system behavior under different conditions and enabled the examination of the temporal evolution of key indicators affecting supply center reliability.

Several simulation scenarios were developed to investigate the potential effects of alternative managerial strategies and policy interventions. These scenarios focused on factors such as environmental risk management, green innovation development, technology adoption, transparency enhancement, cultural development, and sustainability-oriented policies. Scenario analysis enabled the assessment of "what-if" conditions and provided insights into the potential outcomes of strategic decisions before their implementation in real organizational environments.

The validity and robustness of the model were evaluated through a comprehensive set of system dynamics validation procedures. These procedures included boundary adequacy testing, structural verification, extreme-condition testing, dimensional consistency assessment, integration error analysis, behavior reproduction testing, and sensitivity analysis. Boundary adequacy testing ensured that all relevant variables and relationships were included within the model scope. Structural verification examined the consistency of causal relationships with theoretical and empirical evidence. Extreme-condition tests evaluated model performance under unusual parameter values. Integration error analysis assessed numerical stability during simulation, while behavior reproduction tests examined the model's ability to generate realistic system behavior patterns. Finally, sensitivity analysis was conducted to determine the influence of key parameters on model outcomes and to evaluate the robustness of simulation results under varying assumptions. Collectively, these analytical procedures ensured the credibility, validity, and practical applicability of the proposed reliability model for green value chain management in manufacturing industries.

3. Findings and Results

At the beginning of the modeling process, the initial framework of the study was developed based on the model presented by Rafati et al. (2025). This preliminary model provided the conceptual foundation for identifying the factors affecting the reliability model of green value chain management in manufacturing industries.

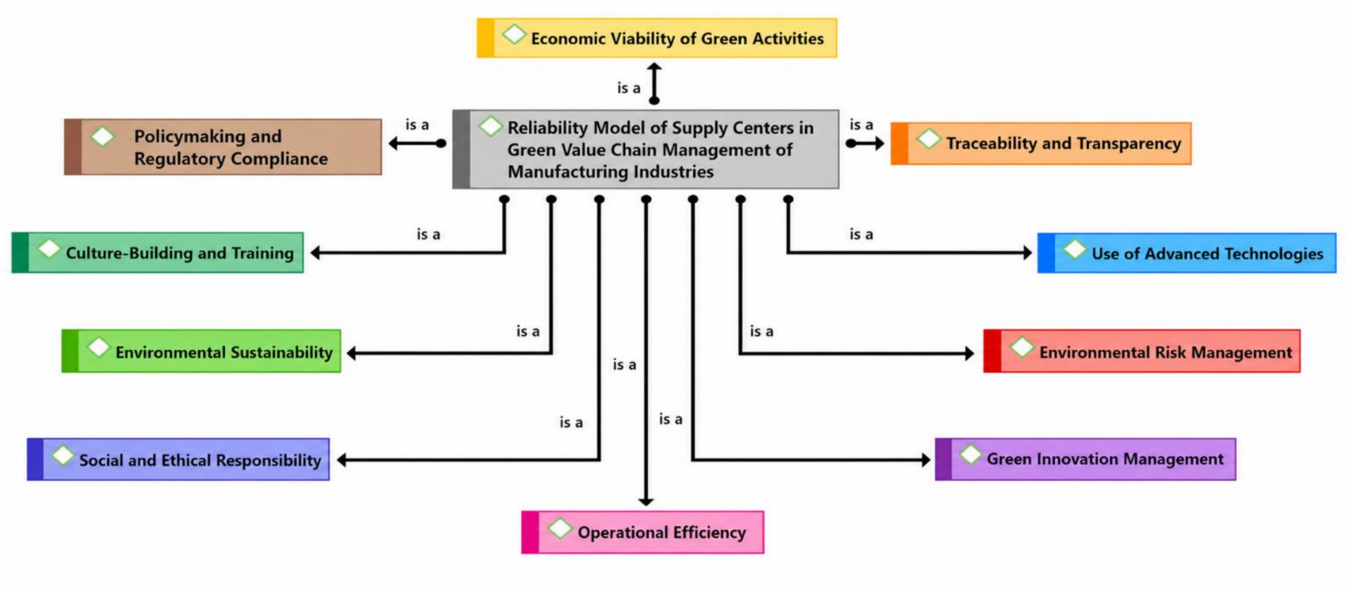

Figure 1. Factors Affecting the Reliability Model of Green Value Chain Management in Manufacturing Industries

Based on the thematic analysis of specialized texts, ten indicators were ultimately identified. To screen these indicators, ensure their importance, and select the final indicators, the Fuzzy Delphi technique was employed. Expert opinions were used to evaluate the importance of the identified indicators. Although experts use their competencies and cognitive abilities to make comparative judgments, the traditional process of quantifying human opinions cannot fully reflect the nature of human thinking. In other words, fuzzy sets are more compatible with linguistic and sometimes ambiguous human judgments; therefore, using fuzzy sets and fuzzy numbers is more appropriate for long-term prediction and real-world decision-making (Karaman et al., 2009). In the present study, triangular fuzzy numbers were used to fuzzify expert judgments. The opinions of experts regarding the importance of each indicator were collected using a seven-point fuzzy scale.

Table 1. Open Coding Symbols Used in the Delphi Technique

Code	Open Coding
C1	Environmental sustainability
C2	Operational efficiency
C3	Social and ethical responsibility
C4	Green innovation management
C5	Traceability and transparency
C6	Environmental risk management
C7	Culture-building and training
C8	Policymaking and regulatory compliance
C9	Use of advanced technologies
C10	Economic viability of green activities

Table 2. Seven-Point Fuzzy Scale for Evaluating the Indicators

Linguistic Variable	Fuzzy Value	Fuzzy Number Scale
Completely unimportant	$\tilde{1}$	(0, 0, 0.1)
Very unimportant	$\tilde{2}$	(0, 0.1, 0.3)

Unimportant	$\tilde{3}$	(0.1, 0.3, 0.5)
Moderate	$\tilde{4}$	(0.3, 0.5, 0.75)
Important	$\tilde{5}$	(0.5, 0.75, 0.9)
Very important	$\tilde{6}$	(0.75, 0.9, 1)
Completely important	$\tilde{7}$	(0.9, 1, 1)

The opinions of 15 experts regarding each indicator were collected and fuzzified. Table 3 presents the fuzzified judgments of the expert panel for each open code. Since the full expert panel included 15 members, the table displays the first three experts and the fifteenth expert as representative entries, while the complete calculation process was based on the judgments of all 15 experts.

Table 3. Fuzzification of Expert Panel Judgments for Each Open Code

Code	Expert 1	Expert 2	Expert 3	...	Expert 15
C1	(0.75, 0.9, 1)	(0.5, 0.75, 0.9)	(0.75, 0.9, 1)	...	(0.9, 1, 1)
C2	(0.9, 1, 1)	(0.5, 0.75, 0.9)	(0.9, 1, 1)	...	(0.9, 1, 1)
C3	(0.75, 0.9, 1)	(0.9, 1, 1)	(0.75, 0.9, 1)	...	(0.9, 1, 1)
C4	(0.1, 0.3, 0.5)	(0.75, 0.9, 1)	(0.9, 1, 1)	...	(0.5, 0.75, 0.9)
C5	(0.9, 1, 1)	(0.75, 0.9, 1)	(0.9, 1, 1)	...	(0.9, 1, 1)
C6	(0.5, 0.75, 0.9)	(0.75, 0.9, 1)	(0.3, 0.5, 0.75)	...	(0.9, 1, 1)
C7	(0.9, 1, 1)	(0.5, 0.75, 0.9)	(0.9, 1, 1)	...	(0.9, 1, 1)
C8	(0.9, 1, 1)	(0.9, 1, 1)	(0.75, 0.9, 1)	...	(0.9, 1, 1)
C9	(0.9, 1, 1)	(0.9, 1, 1)	(0.5, 0.75, 0.9)	...	(0.75, 0.9, 1)
C10	(0.75, 0.9, 1)	(0.9, 1, 1)	(0.75, 0.9, 1)	...	(0.5, 0.75, 0.9)

In the next step, expert opinions were aggregated. Several methods have been proposed for aggregating the judgments of $n$respondents. These aggregation procedures are empirical methods introduced by different researchers. One common approach for aggregating a set of triangular fuzzy numbers is based on the minimum value of l, the geometric mean of m, and the maximum value of u.

The aggregated mean of triangular and trapezoidal fuzzy numbers can usually be summarized by a crisp value representing the best corresponding mean. This operation is referred to as defuzzification. Several methods exist for defuzzification. In most cases, the following simple method is used:

$$x_m^1 = \frac{L + M + U}{3}$$

The values of x_m^ido not differ substantially from one another and are always close to M. Here, Mrefers to the mean obtained from aggregating the most probable values of different triangular fuzzy numbers. Nevertheless, the largest calculated value of $x_m^i$is considered the crisp value (Bojadziev & Bojadziev, 2007). In the present study, the center-of-area method was used for defuzzification as follows:

$$DF_{ij} = \frac{\left(u_{ij} - l_{ij}\right) + \left(m_{ij} - l_{ij}\right)}{3} + l_{ij}$$

The fuzzy means and defuzzified outputs of the indicators are presented in Table 4. A defuzzified value greater than 0.70 was considered acceptable, and any indicator with a value lower than 0.70 was rejected (Wu & Fang, 2011).

Table 4. Results of the First Round of the Delphi Technique for Open Coding

Code	Lower Bound	Most Likely Value	Upper Bound	Fuzzy Mean	Crisp Value	Round 1 Result
C1	0.604	0.754	0.854	(0.604, 0.754, 0.854)	0.738	Accepted
C2	0.833	0.956	0.996	(0.833, 0.956, 0.996)	0.928	Accepted
C3	0.623	0.796	0.913	(0.623, 0.796, 0.913)	0.777	Accepted
C4	0.660	0.825	0.923	(0.660, 0.825, 0.923)	0.803	Accepted
C5	0.771	0.917	0.983	(0.771, 0.917, 0.983)	0.890	Accepted
C6	0.815	0.944	0.996	(0.815, 0.944, 0.996)	0.918	Accepted
C7	0.733	0.894	0.971	(0.733, 0.894, 0.971)	0.866	Accepted
C8	0.840	0.960	0.996	(0.840, 0.960, 0.996)	0.932	Accepted
C9	0.706	0.871	0.965	(0.706, 0.871, 0.965)	0.847	Accepted
C10	0.788	0.923	0.977	(0.788, 0.923, 0.977)	0.896	Accepted

At this stage, the crisp values of all factors were higher than 0.70. Therefore, none of the indicators was removed, and all ten indicators were retained in the final model.

The system dynamics method was used to design the causal relationship pattern of the reliability model of green value chain management in manufacturing industries. System dynamics is an approach for understanding the nonlinear behavior of complex systems over time through feedback loops. This method was introduced by Jay Forrester in *Industrial Dynamics* in 1961 and rapidly expanded thereafter. To design a dynamic system, the variables of the model must first be identified. A closed boundary refers to the scope that clearly separates the variables of a dynamic problem from unrelated variables. Each closed boundary contains feedback loops that affect one another. The resultant effect of these loops forms the behavior of interest. Each feedback loop functions as a fundamental building block of the system structure. This theory stands against the traditional view that considered the flow of influence among phenomena as one-directional. System dynamics emerges from feedback loops; therefore, the modeler must attempt to convert chains of cause-and-effect relationships into causal loops. The continuity of system dynamics requires the existence of causal loops. In this study, Vensim software was used to design the system dynamics model.

Table 5. Components of the Model

No.	Model Component
1	Environmental sustainability
2	Operational efficiency
3	Social and ethical responsibility
4	Green innovation management
5	Traceability and transparency
6	Environmental risk management
7	Culture-building and training
8	Policymaking and regulatory compliance
9	Use of advanced technologies
10	Economic viability of green activities

Calculating the effect of internal relationships on indicator weights is the most important part of examining the influence of internal relationships among indicators in the final selection of the model. Therefore, it was necessary to reconsider how the corresponding weights were calculated. As stated in previous sections, the weight of indicators is calculated as follows:

$$W = R_{ij} \times d_i$$

In this equation, Wdenotes weight, Rrepresents the values assigned to the relationship between a requirement and a technical-engineering specification, $d$indicates the importance degree of the requirement, $i$refers to the related requirement, and $j$refers to the related specification. In the first matrix of this study, ten components were identified.

To improve interpretability, the values obtained from the Delphi analysis can be normalized. However, normalization is feasible only when the components are independent of one another. Therefore, to understand the relationship among components, the variable $\gamma$was defined as the internal relationship among the identified components. Finally, using the following equation, the new values can be calculated by normalizing Rwhile considering the internal relationships among the specifications:

$$R''_{ij} = \frac{\left(\sum_{k=1}^{n} \gamma_{kj}\right) R_{ij}}{\sum_{j=1}^{n} \left[\left(\sum_{k=1}^{n} \gamma_{kj}\right) R_{ij}\right]}$$

In this equation, $k$and $j$represent the technical-engineering specifications. In addition, when $k = j$, then:

$$\gamma_{kj} = 1$$

As discussed, the degree of importance is also directly related to the model. Therefore, it was necessary to formulate a relationship for applying the effect of βon the degree of importance. For this purpose, the following normalized equation was used:

$$d''_i = \frac{\left(\sum_{l=1}^{m} \beta_{il}\right) d_i}{\sum_{i=1}^{m} \left[\left(\sum_{l=1}^{m} \beta_{il}\right) d_i\right]}$$

In this equation, βrepresents the relationship between two requirements, $i$and l. Consequently, by considering the above relationships, the new weights, which are modified based on the internal relationships among the model components, can be calculated using the following equation:

$$W_j'' = \sum_{i=1}^{m} d_i'' R_{ij}''$$

Increasing green innovation leads to greater use of advanced technologies. These technologies improve productivity and consequently reduce environmental impacts. This process increases the sense of social responsibility and reinforces support for green innovation. The loop is defined as follows:

Green Innovation → Advanced Technologies
→ Operational Efficiency
→ Environmental Sustainability
→ Social Responsibility
→ Motivation for Green Innovation

Green innovation refers to new processes aimed at reducing negative environmental impacts and optimizing the use of resources. In this regard, advanced technologies play a key role in facilitating these innovations. The use of modern technologies, such as renewable energy, clean technologies, and smart production systems, enables companies to optimize their production processes in a way that reduces both the consumption of natural resources and negative environmental impacts. These innovations not only improve environmental performance but can also reduce operational costs and thereby increase operational efficiency. For example, using smart production systems can reduce waste, optimize energy consumption, and decrease pollutants.

Increased operational efficiency means continuous improvement of production processes, which can be achieved through green innovations and the use of advanced technologies. This increase in efficiency reduces costs, improves product quality, and ultimately decreases resource and energy consumption, thereby contributing to environmental sustainability. When companies use advanced technologies and green processes to optimize production, these changes not only increase productivity but also directly improve environmental conditions. For example, reducing energy consumption and pollutant generation can help conserve natural resources and reduce the impacts of climate change, which ultimately enhances long-term environmental sustainability.

Corporate social responsibility is one of the critical components of the green innovation process. Companies that attend to their social responsibilities in environmental protection and ethical conduct not only gain competitive advantages in the market but also develop stronger incentives to invest in green innovation. This social responsibility encourages organizations to continuously improve their processes and products through advanced technologies in order to reduce negative environmental impacts and contribute to sustainable development. Motivation for green innovation is usually shaped through external pressures, such as social and legal demands, as well as long-term economic benefits. This positive cycle of innovation, operational efficiency, environmental sustainability, and social responsibility not only creates economic advantages but also becomes a strong driver for the continuation of green innovation in organizations.

Effective policymaking reduces environmental risks and increases transparency within the value chain. This leads to improved sustainability and, in turn, reduces political pressure and the need for further interventions. The relationships in this loop are defined as follows:

Policymaking and Regulations
→ Reduction of Environmental Risks
→ Increased Transparency and Traceability
→ Improved Environmental Sustainability
→ Reduced Political Pressure for Further Regulation

Policymaking and regulations function as one of the main pillars of environmental risk management. Environmental regulations require organizations and industries to comply with specific standards aimed at preserving natural resources and reducing pollution. These policies may include restrictions on greenhouse gas emissions, waste management requirements, or optimized use of energy resources. Following these regulations, industries are required to adopt and implement green processes that directly reduce environmental risks. For example, restrictions imposed on pollutants help reduce the negative effects of production processes and prevent environmental crises. Consequently, organizations must comply with these regulations to reduce environmental hazards and prevent damage to ecosystems.

Increased transparency and traceability in production and organizational processes allow governmental institutions and society to become aware of how environmental regulations are observed and how they affect the environment. This transparency can be achieved through accurate reporting, pollutant monitoring, and examination of production processes. By establishing traceability systems, companies can continuously monitor their activities and ensure their compliance with environmental standards. Increased transparency not only improves public trust and international cooperation but also directly affects environmental sustainability. When organizations manage their processes transparently, they are able to reduce waste, optimize resource consumption, and decrease energy use, all of which improve long-term environmental sustainability.

When organizations and industries effectively comply with environmental regulations and show tangible progress in reducing environmental impacts, political pressure for stricter regulations decreases. This is due to positive performance and organizational commitment to environmental sustainability principles. If industries actively seek to reduce risks and enhance transparency in their activities, governments may perceive less need to impose additional regulatory pressure. This process creates a positive cycle in which industries and organizations reduce political pressure through better implementation of regulations while simultaneously improving environmental sustainability in their production processes. This positive interaction among policymaking, transparency, and reduced political pressure enables society and governmental institutions to collaborate in environmental protection without relying on increasingly strict regulatory mechanisms.

Training and culture-building enhance ethical responsibility among employees. This leads to greener operational behaviors, which in turn improve sustainability and further strengthen green culture. The relationships in this loop are defined as follows:

Culture-Building and Training
→ Increased Ethical Responsibility
→ Improved Green Operational Behaviors
→ Increased Environmental Sustainability
→ Strengthened Green Organizational Culture

Culture-building and training are fundamental to shaping ethical responsibility in organizations and industries. When employees and managers become aware of the importance of environmental sustainability and their ethical responsibilities toward the environment, this awareness leads to changes in their individual and collective behaviors. Continuous training in environmental issues and green ethics can help employees understand how their activities affect natural resources and the environment. Therefore, increased ethical responsibility through culture-building can encourage individuals, not only at the personal level but also at the organizational level, to attach greater importance to their environmental responsibilities. This contributes to the promotion of green operational behaviors and the adoption of more optimal production and consumption practices in organizations.

When organizational culture changes in such a way that ethical and environmental responsibility become priorities, employees and managers become more inclined to improve green operational behaviors. These behaviors include optimal use of resources, reduced energy consumption, reduced waste generation, and pollution prevention. Such operational measures can have positive effects on environmental sustainability because every positive change in operational behavior can reduce negative environmental impacts. For example, reducing water and energy consumption in production processes, using recycled materials, and decreasing production waste directly contribute to environmental sustainability. Moreover, these changes make organizations more responsible in responding to social and environmental pressures for the conservation of natural resources and the reduction of pollution.

Strengthening green organizational culture as a direct outcome of training and culture-building creates greater commitment to environmental sustainability at the organizational level. This green culture is continuously promoted throughout the organization so that all members, from senior managers to operational employees, actively cooperate to improve green processes and reduce environmental impacts in their activities. Such a culture not only facilitates the improvement of green operational behaviors but also strengthens ethical responsibility within the organization. Ultimately, a strong green culture enables organizations to achieve their environmental goals sustainably and consistently and to be recognized as leaders in sustainability. This can create a positive work environment, increase employee satisfaction, and improve overall organizational performance.

The more economically viable green activities become, the greater the tendency to use advanced technologies. As productivity increases, costs decrease, and the economic advantage of green activities is further enhanced. The relationships in this loop are defined as follows:

Economic Viability of Green Activities
→ Increased Use of Advanced Technologies
→ Increased Operational Efficiency → Reduced Costs
→ Increased Economic Viability of Activities

The economic viability of green activities refers to the simultaneous optimization of resource use and cost reduction while preserving the environment. In today's world, many organizations have realized that green activities can generate substantial economic benefits. These benefits are obtained not only through reduced waste and energy consumption but also through the optimization of production processes and the use of advanced technologies. The use of modern technologies, such as smart systems, optimized machinery, and new renewable energy methods, makes green processes more efficient while saving costs and resources. This enables organizations to reduce their negative environmental impacts while simultaneously increasing productivity.

The increased use of advanced technologies directly leads to improved operational efficiency in organizations. New technologies allow organizations to optimize their production processes and reduce waste and energy consumption. This optimization not only reduces long-term costs but also provides organizations with considerable competitive advantages in the market. For example, the use of energy management systems and industrial automation can reduce energy consumption, decrease production time, and optimize human resources. As a result, cost reduction enables organizations to allocate resources more effectively and use their potential capacities more efficiently.

The combination of the economic viability of green activities and increased operational efficiency leads to further improvement in the economic viability of activities. When organizations use advanced technologies to optimize processes and reduce costs, they continuously improve their profitability. These economic improvements help organizations consume resources more efficiently and allow them to operate in competitive markets with higher productivity and lower costs. At the same time, these activities enable organizations to be recognized as pioneers in green activities and environmental sustainability, which can attract new investors and customers and enhance brand reputation. This positive interaction among advanced technologies, operational efficiency, and cost reduction helps organizations make their green activities profitable not only from an environmental perspective but also from an economic perspective.

As traceability increases, environmental risks decrease, which improves trust in the value chain. Greater trust increases acceptance by the market and regulators, releasing more resources for improving transparency systems. The relationships in this loop are defined as follows:

Transparency and Traceability
→ Reduction of Environmental Risks
→ Increased Value Chain Reliability
→ Increased Acceptance by Market and Regulators
→ Support for Improving Traceability Systems

Transparency and traceability serve as key tools in environmental risk management. When organizations establish transparent systems for monitoring and tracing their processes, they can identify environmental problems before major crises occur. Transparency allows organizations to monitor pollution, resource consumption, and waste at each stage of production and to implement corrective measures when necessary. Accurate traceability systems make it possible to record and examine resource consumption and environmental impacts at every stage of the supply chain. Through this mechanism, environmental risks are reduced, and organizations can more accurately prevent environmental damage. These actions increase awareness of the environmental effects of industrial and production activities and reduce their negative impacts.

By reducing environmental risks through transparency and traceability, value chain reliability increases. When organizations can provide accurate and transparent information about their processes, greater trust is created among various stakeholders, including suppliers, consumers, and regulators. This trust not only improves business relationships but also directly affects market acceptance and regulatory support. Consumers and regulators provide more support to organizations that demonstrate higher transparency in their processes and products. In today's context, where consumers and regulatory authorities have become more sensitive to social and environmental responsibility, transparency can become a major competitive advantage. Organizations that have reduced environmental risks and created transparency in their activities are more likely to benefit from market and regulatory support.

Acceptance by the market and regulators ultimately supports the improvement of traceability and monitoring systems in organizations. When organizations use these systems effectively and achieve positive results, the market and regulatory authorities encourage and reinforce such systems. This support may include financial facilities, tax reductions, or even public recognition and awards from governmental authorities. In addition, continuous improvement in traceability systems enables organizations to better manage resources, optimize energy consumption, and reduce pollution. As a result, this process allows organizations not only to increase efficiency and reduce costs but also to contribute to environmental sustainability. In the long term, such support contributes to sustainable organizational growth and strengthens the organization's position in the market and against competitors.

Causal loop diagrams provide a visual understanding of the system structure; however, these diagrams are not sufficient for examining system behavior over time. To better understand system behavior, the relationships among system variables must be formulated, and the values of the variables must be simulated over time. For this purpose, flow diagrams should be designed. Drawing the causal loop model is performed qualitatively, but at this stage quantitative methods must be applied. Formulation means expressing the relationships among the variables of the conceptual model in the form of mathematical relationships based on the stock-and-flow diagram. The general relationships in this model were defined according to the ten components of the reliability model of green value chain management in manufacturing industries.

Environmental sustainability refers to the preservation of natural resources, pollution reduction, and optimal use of energy resources in production processes. In a system dynamics model, this component can influence other components because it is directly related to optimal resource use, waste reduction, and increased environmental productivity. Environmental sustainability can improve operational efficiency, strengthen social and ethical responsibility, and reinforce green innovations.

Operational efficiency refers to the ability of industries to perform production processes with the lowest cost and highest quality. This component affects process improvement and waste reduction and leads to reduced resource consumption and increased productivity. Operational efficiency can contribute to environmental sustainability and influence the use of advanced technologies and green innovation management.

Social and ethical responsibility refers to corporate actions and decisions aligned with social interests and ethical principles. This component is particularly important in manufacturing industries because it can affect brand reputation, customer relationships, and financial performance. It can contribute to increased transparency and traceability, the development of a positive organizational culture, and the strengthening of environmental risk management.

Green innovation management refers to the development and implementation of new green technologies and processes that help reduce the environmental impacts of production. Green innovation may include modern technologies in production processes, renewable energy, and pollutant reduction. It can improve environmental sustainability and operational efficiency and provide companies with greater competitive capacity.

Traceability and transparency refer to the ability to accurately track and report information related to production processes, consumed resources, and environmental impacts. This component improves organizational transparency and optimal decision-making. It can affect all parts of the model, particularly environmental sustainability, operational efficiency, and social responsibility.

Environmental risk management refers to identifying, evaluating, and reducing negative environmental risks arising from industrial activities. These risks include pollution, climate change, and excessive resource consumption. This component can strengthen green innovation, environmental sustainability, and social responsibility.

Culture-building and training refer to processes of information dissemination, education, and attitude change regarding environmental and social responsibilities. This component can change organizational behavior and increase awareness of environmental and social issues. Culture-building and training can affect operational efficiency, social responsibility, and environmental risk management and can improve overall organizational performance.

Policymaking and regulatory compliance refer to the establishment of internal and external policies aligned with environmental standards and regulations. This component can ensure organizational compliance with environmental laws and improve organizational credibility. It can affect all components because legal compliance usually requires improvements in traceability, transparency, and risk management.

The use of advanced technologies refers to the adoption of new technologies for optimizing processes, reducing pollutants, and increasing productivity. This component plays an important role in green innovation and reducing production costs. The use of advanced technologies can improve operational efficiency, reduce environmental risks, and enhance environmental sustainability.

The economic viability of green activities refers to the cost–benefit logic of environmental activities, including optimized resource consumption, reduced energy costs, and high returns on green investments. This component contributes to cost reduction and profitability and can encourage the use of advanced technologies, green innovation management, and environmental sustainability. Ultimately, the general causal loop model was determined as follows.

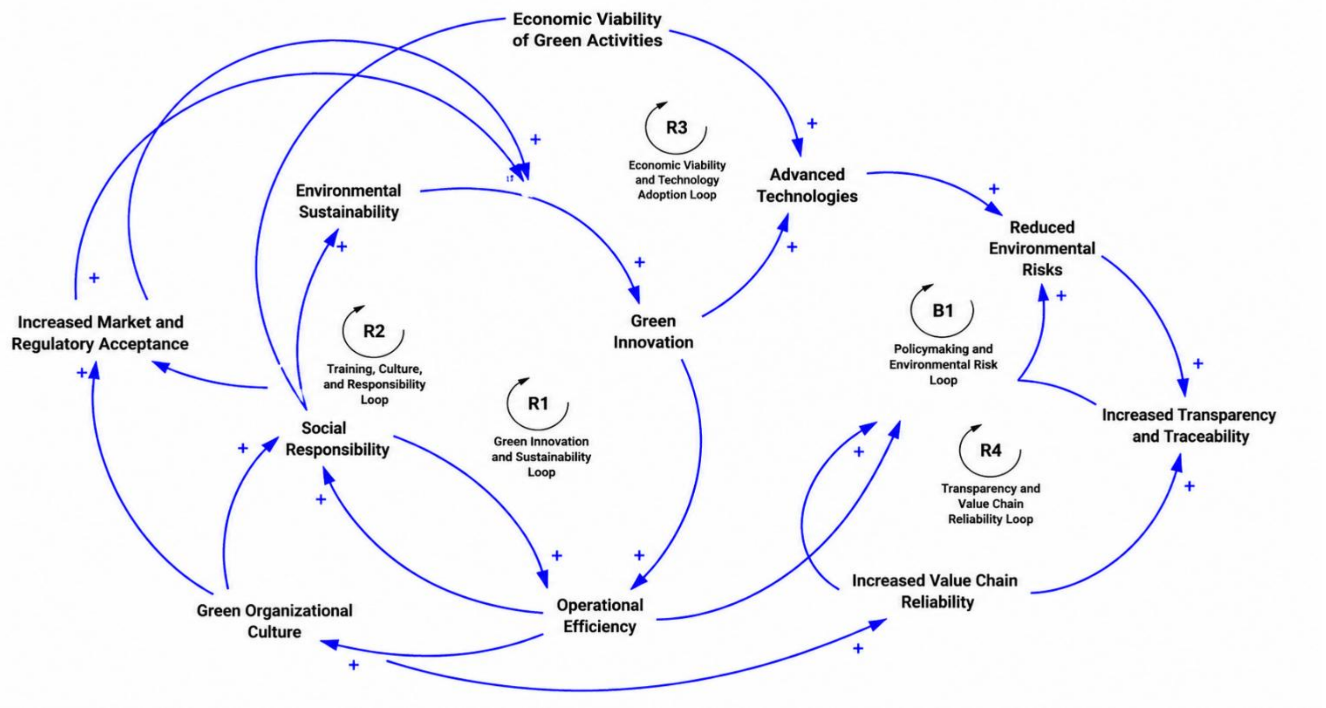

Figure 2. General Causal Loop Diagram

The research variables were divided into three main categories: endogenous variables, exogenous variables, and auxiliary variables, which combine endogenous and exogenous aspects. After analyzing the model, state variables, rate variables, and the measurement scale of the variables were identified. Table 6 presents the variables used in the systemic model of the study.

Table 6. Variables Used in the Systemic Model of the Study

Model Component	Description	Variable Type	Variable Formula	Unit of Measurement
Environmental sustainability	Environmental sustainability refers to the capacity to preserve natural resources and ecosystems for future generations and is evaluated based on optimal resource use and reduction of negative environmental impacts.	State	$\frac{\text{Used resources}}{\text{Environmental impact}}$	Percentage
Operational efficiency	Operational efficiency refers to the degree of process optimization and optimal use of resources such as energy, labor, and materials.	State	$\frac{\text{Consumed resources, including raw materials and energy}}{\text{Produced product}}$	Product unit per unit of energy or raw material
Social and ethical responsibility	Social and ethical responsibility refers to organizational commitment to activities consistent with ethical and social values for improving society and protecting human rights.	State	$\frac{\text{Degree of compliance with ethical criteria}}{\text{Overall performance}}$	Percentage
Green innovation management	Green innovation management refers to processes in which green technologies and innovations are used to reduce negative environmental impacts and increase productivity.	Flow	$\frac{\text{Investment in research and development}}{\text{Number of green innovation operations}}$	Percentage or number
Traceability and transparency	Traceability and transparency refer to the ability to clarify processes,	State	$\frac{\text{Total processes}}{\text{Number of traced processes}}$	Percentage

	resources, and outputs and to identify and track problems and resources in production.			
Environmental risk management	Environmental risk management includes identifying, assessing, and reducing negative environmental risks resulting from industrial activities.	Flow	$\frac{\text{Identified risks}}{\text{Risk reduction actions}}$	Number
Culture-building and training	Culture-building and training refer to processes of information dissemination, training, and attitude change in relation to environmental and social responsibilities.	Flow	$\frac{\text{Number of employees}}{\text{Number of training courses}}$	Training courses per person
Policymaking and regulatory compliance	Policymaking and regulatory compliance refer to compliance with environmental and social laws and regulations at all organizational levels.	State	$\frac{\text{Total environmental laws}}{\text{Number of implemented environmental laws}}$	Percentage
Use of advanced technologies	Use of advanced technologies refers to the adoption of the latest technologies to improve production processes and reduce environmental impacts.	Flow	$\frac{\text{Total number of available technologies}}{\text{Number of technologies used}}$	Number
Economic viability of green activities	Economic viability of green activities refers to optimized costs and profitability derived from green activities, through which environmental and economic productivity are improved.	State	$\frac{\text{Investment costs in green actions}}{\text{Income from green activities}}$	Income-to-cost ratio in green activities

The variables of this study were categorized into three main groups, each playing a specific role in analyzing the reliability model of green value chain management in manufacturing industries. By carefully examining the model, different variables were identified in terms of state, rate, and magnitude, meaning their condition, changes over time, and degree of influence or importance within the system. These classifications were made to better understand the relationships and interactions among the variables and their effects on the reliability model of green value chain management in manufacturing industries. The details presented in Table 6 can serve as a reference for more precise analysis and model implementation in related software environments.

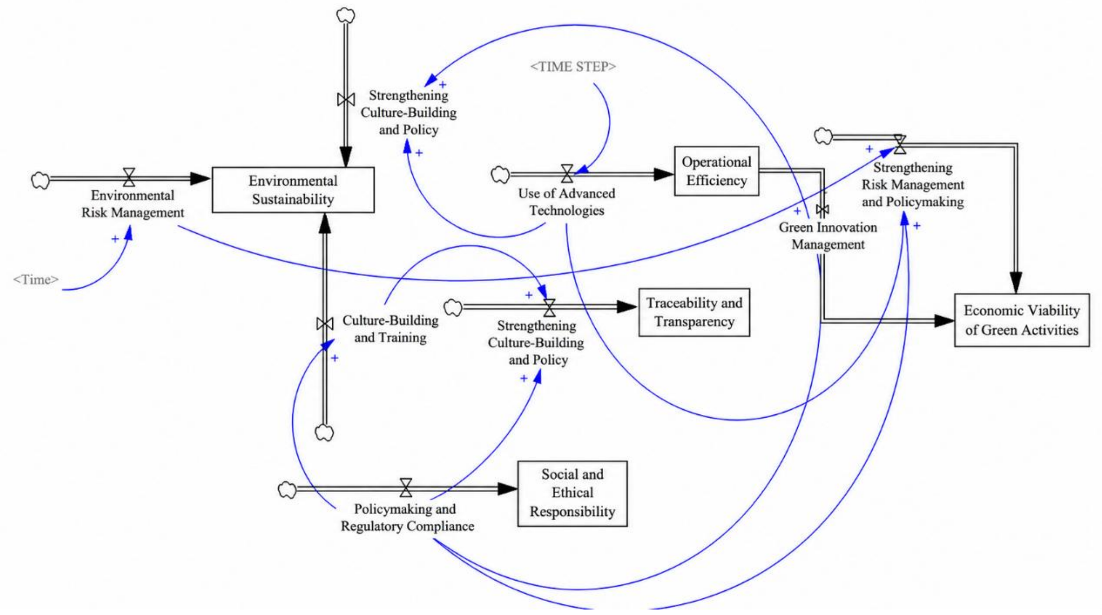

Figure 3. Stock-and-Flow Diagram for Implementing the Reliability Model of Green Value Chain Management in Manufacturing Industries

4. Discussion and Conclusion

The present study aimed to estimate a reliability model for supply centers in green value chain management within manufacturing industries using a System Dynamics approach. The findings revealed that all ten identified components, including environmental sustainability, operational efficiency, social and ethical responsibility, green innovation management, traceability and transparency, environmental risk management, culture-building and training, policymaking and regulatory compliance, utilization of advanced technologies, and the economic viability of green activities, achieved defuzzified values above the acceptance threshold during the fuzzy Delphi process and were therefore retained in the final model. This finding demonstrates that supply center reliability in green value chains is not influenced by a single organizational or technical factor; rather, it emerges from the interaction of multiple technological, environmental, social, economic, and institutional dimensions. This multidimensional perspective is consistent with recent studies emphasizing that successful implementation of green supply chain management requires simultaneous attention to sustainability, innovation, operational performance, and stakeholder expectations [1, 2, 5].

One of the most important findings of the study was the identification of environmental sustainability as a central state variable within the system. The simulation results indicated that environmental sustainability both influences and is influenced by several other variables, creating multiple reinforcing and balancing feedback mechanisms throughout the model. This result supports the argument that sustainability has evolved from a peripheral environmental concern into a strategic organizational capability that shapes long-term competitiveness and resilience. Similar conclusions have been reported in studies examining green supply chain practices and sustainability transformation, which indicate that environmental performance improvements contribute directly to organizational effectiveness, stakeholder trust, and sustainable competitive advantage [1-3]. The current findings further suggest that environmental sustainability acts as a leverage point within manufacturing value chains, meaning that improvements in sustainability generate positive ripple effects throughout the system.

The results also highlighted the critical role of green innovation management in enhancing supply center reliability. The reinforcing loop identified as the “Green Innovation and Sustainability Loop” demonstrated that greater investment in green innovation encourages the adoption of advanced technologies, improves operational efficiency, strengthens environmental sustainability, and ultimately reinforces organizational commitment to further innovation. This dynamic relationship supports previous research emphasizing that innovation serves as a key mechanism for transforming environmental challenges into opportunities for value creation and competitive differentiation [1, 10]. Similarly, studies conducted in manufacturing sectors have shown that green innovation contributes significantly to sustainable development by enabling cleaner production processes, reducing waste generation, and improving resource utilization efficiency [2, 4]. The present study extends this literature by illustrating how innovation creates self-reinforcing cycles that continuously enhance supply chain reliability over time.

Another important finding concerns the role of advanced technologies within the green value chain. The model demonstrated that the utilization of advanced technologies directly improves operational efficiency, traceability, transparency, and environmental performance. Furthermore, technological adoption was found to be strongly associated with the economic viability of green activities, creating additional reinforcing effects throughout the system. These findings are consistent with previous research highlighting the transformative impact of Industry 4.0 technologies, blockchain systems, artificial intelligence, and digital monitoring tools on supply chain performance [17-19]. The findings also support the work of Kim et al. [4], who argued that technology-enabled green supply chain management significantly improves sustainability outcomes in manufacturing industries. By integrating technological and environmental perspectives, the current study demonstrates that digital transformation is not merely an operational improvement strategy but a fundamental driver of sustainable supply chain reliability.

The simulation results further revealed that environmental risk management constitutes a crucial balancing mechanism within the system. The “Policymaking and Environmental Risk Loop” indicated that effective policies reduce environmental risks, increase transparency, improve sustainability outcomes, and subsequently diminish the need for additional regulatory intervention. This finding aligns with studies emphasizing the importance of risk assessment and uncertainty management in sustainable supply chains [7, 8]. Previous research has demonstrated that organizations capable of proactively identifying and mitigating environmental risks experience fewer disruptions, improved stakeholder confidence, and greater resilience in the face of uncertainty [14, 20]. The present study contributes to this literature by showing how risk management interacts dynamically with policymaking and transparency mechanisms to stabilize system behavior over time.

Traceability and transparency emerged as another influential component affecting supply center reliability. The identified feedback structure showed that enhanced traceability reduces environmental risks, increases value chain reliability, improves market acceptance, and generates support for further investments in monitoring and reporting systems. This finding strongly supports previous studies emphasizing the importance of transparency and traceability in modern supply chain systems [6, 17]. Dai et al. [6] reported that traceability mechanisms significantly improve reliability optimization and product recall effectiveness, while blockchain-based studies have highlighted the capacity of digital technologies to improve trust and information sharing across supply networks [17, 18]. The present findings indicate that transparency should not be viewed merely as a reporting requirement but as a strategic capability that enhances both environmental and economic performance.

An additional contribution of the study concerns the role of culture-building and training in promoting socially responsible and environmentally sustainable behaviors. The "Training, Culture, and Responsibility Loop" demonstrated that educational initiatives increase ethical responsibility among employees, improve environmentally responsible operational behaviors, strengthen sustainability performance, and reinforce green organizational culture. These findings are consistent with organizational capability and learning theories, which emphasize the role of knowledge development and cultural transformation in achieving sustainable performance improvements [23, 24]. Research has shown that organizations with strong learning cultures are more capable of adopting innovative practices, responding to environmental challenges, and maintaining long-term competitive advantages [22, 23]. The present study extends these insights by demonstrating that organizational culture functions as a reinforcing mechanism capable of sustaining positive environmental behaviors over extended periods.

The economic viability of green activities also emerged as a fundamental determinant of supply center reliability. The identified feedback relationships indicated that economically beneficial green practices encourage technological investments, improve operational efficiency, reduce costs, and generate additional financial incentives for sustainability initiatives. These results support previous research suggesting that environmental sustainability and economic performance are complementary rather than contradictory objectives [3, 11]. Organizations are more likely to adopt and sustain green practices when these practices demonstrate clear economic benefits through cost reductions, productivity improvements, or enhanced market opportunities. The findings therefore challenge traditional assumptions that environmental investments necessarily impose financial burdens and instead support contemporary perspectives emphasizing shared value creation and sustainable competitiveness [1, 2].

The findings additionally revealed strong interactions among operational efficiency, social responsibility, and regulatory compliance. Organizations exhibiting higher levels of operational efficiency were better positioned to comply with environmental regulations, fulfill social responsibilities, and maintain stakeholder trust. These findings are consistent with prior studies suggesting that operational excellence and sustainability performance are mutually reinforcing rather than independent organizational objectives [12, 29]. Similarly, regulatory compliance was found to facilitate transparency, risk reduction, and sustainability improvements, supporting arguments that effective governance structures play an essential role in advancing green supply chain objectives [5, 9].

From a theoretical perspective, the study contributes to the green supply chain management literature by integrating diverse sustainability dimensions into a unified dynamic framework. While previous research has often examined isolated relationships among environmental, technological, or economic variables, the present model demonstrates that supply center reliability emerges from complex interactions among multiple reinforcing and balancing feedback loops. The results support systems thinking perspectives, which argue that organizational performance cannot be fully understood through linear cause-and-effect relationships alone. Instead, long-term outcomes arise from dynamic interactions among interconnected system components [27]. The System Dynamics methodology therefore provides valuable insights into how sustainability-oriented interventions may produce intended and unintended consequences across manufacturing value chains.

Overall, the findings indicate that supply center reliability in green value chain management is a dynamic and multidimensional phenomenon requiring coordinated attention to environmental sustainability, technological advancement, organizational learning, social responsibility, regulatory compliance, economic viability, and risk management. The interactions among these dimensions create complex feedback structures that influence organizational performance over time. Consequently, managers seeking to improve supply center reliability should adopt integrated and systemic approaches rather than focusing on isolated improvements within individual functions or processes.

Despite its contributions, this study has several limitations. First, the model was developed primarily through expert judgments, literature synthesis, and system dynamics simulation rather than empirical longitudinal observations. Second, the model was designed within the context of manufacturing industries and may not fully capture the characteristics of service-oriented or highly specialized sectors. Third, although the model incorporated ten major variables, other potentially influential factors such as organizational size, international market conditions, geopolitical risks, and macroeconomic fluctuations were not explicitly included. Finally, simulation results depend on the assumptions embedded within the model structure, which may differ from actual organizational conditions in specific industrial settings.

Future studies are encouraged to validate the proposed model using empirical data collected from manufacturing organizations operating in different industries and countries. Researchers may also investigate additional variables such as organizational resilience, digital maturity, stakeholder engagement, circular economy practices, and carbon neutrality initiatives. Comparative studies examining differences between developed and developing economies could provide valuable insights regarding contextual influences on green supply chain reliability. Furthermore, future research could integrate System Dynamics with other quantitative techniques such as structural equation modeling, agent-based modeling, machine learning, or network analysis to develop more comprehensive predictive frameworks.

Managers should adopt a systemic perspective when designing green supply chain strategies and recognize the interconnected nature of environmental, technological, social, and economic factors. Investments in advanced technologies should be accompanied by employee training programs, cultural transformation initiatives, and transparent reporting systems. Organizations should establish proactive environmental risk management mechanisms and continuously monitor sustainability performance indicators. Policymakers can support these efforts by creating regulatory frameworks that encourage innovation, transparency, and sustainable business practices. Finally, manufacturing firms should evaluate green initiatives not only from an environmental perspective but also in terms of their long-term economic benefits, operational improvements, and contributions to organizational reliability.

Authors' Contributions

Authors equally contributed to this article.

Acknowledgments

Authors thank all participants who participate in this study.

Declaration of Interest

The authors report no conflict of interest.

Funding

According to the authors, this article has no financial support.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

References

[1] E. Asiedu, E. Malcalm, and M. Majeed, "Green Supply Chain Management and Sustainable Competitive Advantage: Exploring the Role of Green Ambidexterity Innovation," (in English), *Modern Supply Chain Research and Applications*, vol. 23, no. 4, pp. 1-18, 2026, doi: 10.1108/MSCRA-02-2025-0006.

[2] A. S. Mahar, Y. Zhang, B. Sadiq, and R. F. Gul, "Sustainability Transformation Through Green Supply Chain Management Practices and Green Innovations in Pakistan's Manufacturing and Service Industries," *Sustainability*, vol. 17, no. 5, p. 2204, 2025, doi: 10.3390/su17052204.

[3] S. Mondal, "Green Entrepreneurship in Circular Supply Chain Management: How Success Factors Assist a Zero-Waste Economy," *Business Strategy & Development*, vol. 8, no. 4, 2025, doi: 10.1002/bsd2.70244.

[4] C. Kim, X. Liu, and K. Jeong, "Technology-Enabled Green Supply Chain Management in China's Manufacturing Sector," (in English), *Journal of Manufacturing Technology*

Management, vol. 37, no. 4, pp. 773-794, 2025, doi: 10.1108/JMTM-02-2025-0118.
[5] K. Zarei, E. Mashaikhi Nezam Abadi, and Zarei, "Identification of key factors and success model in implementing green supply chain management in Iran's construction industry," *Dynamic Management and Business Analysis*, vol. 3, no. 4, pp. 1-22, 2025. [Online]. Available: https://www.noormags.ir/view/en/articlepage/2212328.
[6] B. Dai, Y. Nu, X. Xie, and J. Li, "Interactions of Traceability and Reliability Optimization in a Competitive Supply Chain with Product Recall," (in English), *European Journal of Operational Research*, vol. 290, no. 1, pp. 116-131, 2021.
[7] F. A. de Lima, S. Seuring, and P. C. Sauer, "A Systematic Literature Review Exploring Uncertainty Management and Sustainability Outcomes in Circular Supply Chains," (in English), *International Journal of Production Research*, pp. 1-34, 2021.
[8] M. Jafari Eskandari and H. Emami Saloot, "A Multi-Objective Optimization Model for Risk Assessment in a Sustainable Closed-Loop Supply Chain under Parameter Uncertainty: Using the Conditional Value-at-Risk (CVaR) Approach," (in English), *Industrial Management Studies*, vol. 20, no. 66, pp. 251-298, 2022.
[9] M. Nakhaeinejad, A. Dehghan, and N. S. Vaziri, "Developing a supply chain coordination model through a revised revenue sharing contract: Incorporating sales efforts and green quality considerations," *International Journal of Production Management and Engineering*, vol. 13, no. 1, pp. 102-121, 2025, doi: 10.4995/ijpme.2025.20402.
[10] A. Distanont and O. Khongmalai, "The Role of Innovation in Creating a Competitive Advantage," (in English), *Kasetsart Journal of Social Sciences*, vol. 41, no. 1, pp. 15-21, 2020.
[11] J. Falciola, M. Jansen, and V. Rollo, "Defining Firm Competitiveness: A Multidimensional Framework," (in English), *World Development*, vol. 129, p. 104857, 2020.
[12] E. Saadi, K. Fathi Hafshejani, and R. Radfar, "Designing a Multi-Objective Closed-Loop Supply Chain Mathematical Model with a Supplier Selection Approach and Discount Consideration," (in English), *Engineering Management and Soft Computing*, vol. 7, no. 2, pp. 73-113, 2022.
[13] M. Shahriari and M. Gholami, "Competition between Manufacturer and Retailer in Collecting Returned Products under Greening and Product Quality Improvement in a Closed-Loop Supply Chain," (in English), *Production and Operations Management*, vol. 13, no. 3, pp. 137-158, 2022.
[14] M. Bagheri and N. Javadian, "Presenting a Model for Optimizing a Multi-Level Closed-Loop Supply Chain Network," Iran University of Science and Technology, 2022.
[15] S. Bani Fazel, M. A. Babaei Zakliki, and M. Hosseinzadeh Shahri, "Presenting a Model for Agile Supply Chain Using a Meta-Synthesis Approach," (in English), *Management Research in Iran*, vol. 25, no. 3, pp. 26-49, 2021.
[16] S. N. Seydaei Gol Sefidi, "Examining the Effect of Supply Chain Agility on Competitive Advantage: Case Study of Chaharmahal and Bakhtiari Automotive Sheet Company," (in English), *New Research Approaches in Management and Accounting*, vol. 5, no. 17, pp. 137-151, 2021.
[17] P. Dutta, T. M. Choi, S. Somani, and R. Butala, "Blockchain Technology in Supply Chain Operations: Applications, Challenges and Research Opportunities," (in English), *Transportation Research Part E: Logistics and Transportation Review*, vol. 142, p. 102067, 2020.
[18] C. Dang, F. Wang, Z. Yang, H. Zhang, and Y. Qian, "Evaluating and Forecasting the Risks of Small to Medium-Sized Enterprises in the Supply Chain Finance Market Using Blockchain Technology and Deep Learning Model," (in English), *Operations Management Research*, 2022.
[19] H. Fatorachian, "Impact of Industry 4.0 on Supply Chain Performance," (in English), *Production Planning & Control*, vol. 32, no. 1, pp. 63-81, 2021.
[20] M. Ramazani, I. Mahdavi, and E. Babaei, "A New Model for Designing an Antifragile-Sustainable Closed-Loop Supply Chain Network," Mazandaran University of Science and Technology, 2022.
[21] A. Pazhoohandeh and G. Mohammadi Khashoei, "Designing a Two-Stage Stochastic Network Model for a Periodic Multi-Product Green Closed-Loop Supply Chain and Examining the Interactions of Objective Functions," in *Proceedings of the 1st International Summit on Challenges and Modern Solutions in Industrial Engineering, Management and Accounting*, Sari, 2020.
[22] E. Roshan Ghiyas, R. Sepahvand, A. Gholami Chenarestan Olia, and A. Pirzad, "Designing a Model to Examine the Relationship between Organizational Capabilities, Competitive Advantage, and New Product Performance: A Case Study of Firms Active in the Food Industry in Mashhad," (in English), *Productivity Management*, vol. 15, no. 56, pp. 243-263, 2021.
[23] V. Dalvand, R. Sepahvand, and A. H. Nazarpouri, "The Effect of Intellectual Capital on Competitive Advantage and Organizational Performance with the Mediating Role of Innovation and Learning Culture among Faculty Members of Lorestan University," ed, 2021.
[24] N. Seifollahi and V. Ebrahimi Kharajoo, "Analyzing the Moderating Role of Knowledge Management in the Relationship between Intellectual Capital and Brand Competitive Advantage: Focusing on the Mediating Role of Brand Value; Research Sample: Hotels in Ardabil," (in English), *Organizational Knowledge Management*, vol. 4, no. 15, pp. 151-182, 2021.
[25] E. Amouamouha and N. Yazdani, "The Effect of Marketing Capabilities on Export Firm Performance through Competitive Strategy and Positional Advantage with the Moderating Role of Ambidextrous Innovation," (in English), *Strategic Management Studies*, no. 45, pp. 65-82, 2021.
[26] C. N. Chiu and C. L. Yang, "Competitive Advantage and Simultaneous Mutual Influences between Information Technology Adoption and Service Innovation: Moderating Effects of Environmental Factors," (in English), *Structural Change and Economic Dynamics*, vol. 49, pp. 192-205, 2019.
[27] M. Atefi, R. Radfar, and E. Asgharizadeh, "Presenting a Dynamic Model for Evaluating the Degree of Leagility in Performance," ed, 2021.
[28] H. Damghanian, M. Keshavarz, H. Esmailian, M. Hassanzadeh, and Zohreh, "Examining the Relationship among Demand Uncertainty, Strategic Partnership, and Human Resource Outsourcing in Achieving Competitive Advantage," (in English), *Human Resource Development and Support Management Quarterly*, vol. 16, no. 60, pp. 55-82, 2020.
[29] C. Y. Chiu, C. Y. Cheng, and T. Y. Wu, "Integrated Operational Model of Green Closed-Loop Supply Chain," (in English), *Sustainability*, vol. 13, p. 6041, 2021.