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Dynamic Modeling of the Reverse Logistics Supply Chain for Gas Refining Industry Waste Management

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ABSTRACT

This study aimed to design and present a dynamic model for industrial waste management in Iran's gas refining industry using the reverse logistics supply chain approach. The main objective was to identify key factors affecting this chain and provide solutions to improve efficiency and reduce costs associated with industrial waste management. The research method combined grounded theory and system dynamics. In the first stage, semi-structured interviews were conducted with 17 academic experts and managers in the gas refining industry to identify the key variables influencing the reverse logistics supply chain. These variables were then categorized into a paradigmatic model. In the second stage, the relationships among these variables were dynamically modeled using Vensim software. This modeling process examined the impact of different variables on the efficiency of the supply chain and the costs of waste management. The findings indicated that improving infrastructure, advancing recycling technologies, and achieving alignment among the components of the supply chain can significantly enhance the efficiency of the reverse logistics supply chain and reduce industrial waste management costs. Moreover, increasing employee training and top management support were identified as critical facilitators for the success of this system. Sensitivity analysis results also confirmed that improving community satisfaction and reducing environmental pollution directly affect system performance. This dynamic model can serve as an effective decision-making tool for industrial waste management and the improvement of supply chain sustainability. Enhancing infrastructure, recycling technologies, alignment among supply chain components, employee training, and top management support are among the key factors that can significantly improve system efficiency and reduce costs. Additionally, emphasizing community satisfaction and reducing environmental pollution are highlighted as essential elements in the success of industrial waste management systems. This study may also serve as a foundation for future research and improvements in waste management systems across other industries.

Keywords: Reverse logistics supply chain, industrial waste management, system dynamics, grounded theory, dynamic modeling

Introduction

Knowledge-based companies (KBCs) have emerged as strategic drivers of innovation, economic diversification, and sustainable competitiveness in knowledge economies. These organizations generate value primarily through intellectual capital and the application of specialized knowledge to create innovative products and services [1]. Governments and research institutions increasingly recognize the potential of KBCs to contribute to national economic resilience, technological self-reliance, and high-quality employment opportunities. In the Iranian context, the establishment and growth of KBCs has been prioritized as a central pillar for economic transformation beyond oil dependency and for integrating local innovations into global markets [2]. However, despite ambitious policy efforts, the development trajectory of these enterprises is uneven, particularly due to fragmented support structures, legal and regulatory ambiguities, and limited integration with entrepreneurial ecosystems [3, 4].

A knowledge-driven economy requires robust and adaptive policies that align with the dynamic realities of technology-intensive businesses [5]. Policies must address the complexity of innovation processes, from early-stage research and knowledge generation to commercialization and international market entry. Scholars emphasize that knowledge-based leadership and advanced knowledge management practices significantly influence organizational performance, but these require coherent institutional support [3, 6]. In the absence of consistent policy guidance, companies face difficulties navigating regulatory requirements, obtaining tailored financing, and protecting intellectual property [7]. Moreover, the volatile economic environment, including currency fluctuations and high financing costs, compounds these challenges and discourages long-term investment in research-driven enterprises [8].

International literature shows that linking technology adoption and corporate entrepreneurship to external knowledge networks can strengthen innovation capacity and market positioning [9]. For instance, digital platforms and open innovation networks have enabled small and medium-sized KBCs to access expertise and resources beyond their internal boundaries [5]. In Iran, however, the full potential of digital transformation for entrepreneurial success is underutilized, partly due to limited policy integration and insufficient support for digital business ecosystems [10]. Scholars have argued that adopting digital entrepreneurship frameworks could help KBCs overcome market isolation and increase resilience under conditions of international sanctions and global competition [11].

Another critical dimension in strengthening KBCs involves the development of entrepreneurial ecosystems that link universities, research institutions, investors, and regulatory bodies [12]. Universities, in particular, play a pivotal role in fostering knowledge-oriented entrepreneurship by serving as sources of talent, research, and spin-off ventures [13]. Yet, the translation of academic knowledge into viable business ventures remains challenging due to weak support mechanisms, insufficient entrepreneurship education, and a lack of adaptive financing models [13, 14]. Research suggests that robust knowledge transfer processes, mentorship, and innovation-oriented curricula are necessary to build the employability skills and entrepreneurial orientation required in KBCs [4, 15].

In addition to human capital development, effective governance is a crucial enabler. Stable, transparent, and adaptive regulatory frameworks help reduce uncertainty for entrepreneurs and investors [7]. Flexible taxation and customs regimes can lower entry barriers for advanced technologies and raw materials, while intellectual property protection incentivizes innovation [2, 16]. In Iran, however, entrepreneurs often report inconsistencies in the application of supportive policies and a lack of coordination among governmental agencies [3]. Some programs exist to facilitate access to knowledge networks and funding, but they are fragmented and insufficiently integrated with private sector mechanisms [17]. This has implications for entrepreneurial persistence, as knowledge workers facing career plateauing or policy uncertainty are more likely to disengage or exit innovative ventures [17].

The rapid pace of global technological development intensifies the urgency of designing responsive policy models. As Chen et al. [5] demonstrate, digital business ecosystems require integrated frameworks that combine the knowledge-based view of the firm with ecosystem-level collaboration. Without adaptive support, knowledge-intensive firms risk lagging behind international competitors and missing opportunities for cross-border innovation alliances [18]. Recent Iranian studies show that KBCs can play an instrumental role in international entrepreneurship by leveraging localized innovation to enter global markets, provided that government and ecosystem actors facilitate partnerships and reduce transactional barriers [10, 18].

Economic volatility and external shocks further highlight the vulnerability of KBCs to policy gaps [8]. The inability to hedge against exchange rate fluctuations and inflation can undermine research continuity and commercial scaling. Entrepreneurs require policy frameworks that not only support innovation but also build resilience against macroeconomic and political risks [11]. In this regard, flexible funding models, crisis-oriented support measures, and stronger international collaborations can help mitigate external constraints. Moreover, the political environment and global positioning of Iran influence the extent to which KBCs can engage in technology transfer, secure strategic partnerships, and integrate into global value chains [9].

Given these multidimensional challenges, scholars argue for systemic policy approaches that go beyond piecemeal initiatives [4, 6]. A grounded theory approach is particularly useful for unpacking the complex relationships among regulatory, economic, cultural, and organizational factors shaping KBC development [11, 16]. By directly engaging experts and practitioners, such research can identify not only the structural barriers but also context-specific enablers for knowledge-driven entrepreneurship. Several Iranian studies have successfully applied grounded theory to develop strategic models for digital entrepreneurship, sports-based knowledge enterprises, and regional development of KBCs [2, 11, 16]. These frameworks offer valuable methodological precedents for designing a comprehensive policy model.

Another key aspect emerging from the literature is the integration of internal organizational dynamics with ecosystem-level conditions [3, 9]. Internal knowledge management systems, when supported by external policy incentives, can significantly enhance product innovation and market adaptability. Bahari and Taheri Rouzbahani [4] demonstrate that electronic human resources management and knowledge creation practices strengthen organizational agility in KBCs, but their effectiveness depends on enabling macro policies. Similarly, Mousavi Shamsabad et al. [6] emphasize that knowledge management functions improve efficiency across supply chains but require coherent strategies and resource allocation. Thus, policy frameworks should align organizational knowledge-based leadership with national innovation goals.

Furthermore, the role of entrepreneurship education is consistently highlighted as a bridge between knowledge production and commercial application [13, 15]. Strengthening employability capabilities, fostering an entrepreneurial mindset, and equipping talent with commercialization skills can help KBCs overcome early-stage survival challenges and accelerate growth [14]. Policies that integrate educational initiatives, incubation, and mentorship within university and regional ecosystems can improve the innovation pipeline and reduce the gap between research and market success [12].

Despite these advances, there remains a significant gap in designing a unified, context-sensitive model that captures the interplay of causal, contextual, and intervening conditions impacting KBC development in Iran. Prior research has either focused narrowly on organizational enablers [3, 4] or addressed isolated policy instruments [2, 10], leaving an unmet need for an integrative paradigm. A grounded theory approach that systematically builds on expert insights and synthesizes existing conceptual frameworks is critical to overcoming this fragmentation [11]. Such an approach can generate actionable strategies for commercialization, facilitation, and leadership while accounting for the economic and political complexities of Iran's innovation ecosystem [5, 9].

In light of these issues, this study seeks to identify and conceptualize the components of policy models that effectively support the creation and development of knowledge-based companies in Iran.

Methodology

This study aimed to propose and design a comprehensive dynamic model for managing industrial wastewater and waste in the gas refining industry in Iran by combining two qualitative and quantitative methods: **grounded theory** and **system dynamics**.

In the first phase, grounded theory was applied to collect data through in-depth semi-structured interviews with 17 academic experts and senior managers in the gas refining industry. These interviews led to the identification of key variables affecting the reverse logistics supply chain, which were categorized into a paradigmatic model consisting of causal conditions, contextual conditions, strategies, intervening/facilitating conditions, and outcomes.

In the second phase, using system dynamics and Vensim software, the relationships among the identified variables were dynamically modeled. This modeling enabled the analysis of complex interactions among economic, environmental, and social factors. Through the construction of cause-and-effect diagrams and stock-and-flow diagrams, the system's behavior over time was simulated.

This combined methodological approach provided the ability to analyze various scenarios and support decision-makers in selecting optimal solutions for improving industrial waste management. Additionally, sensitivity analysis was conducted to examine the impact of changes in key parameters such as the rate of community satisfaction improvement and reduction of environmental pollution on system performance. This comprehensive and systematic approach not only contributes to a better understanding of the dynamic interactions among various factors but also offers a powerful tool for strategic decision-making in industrial waste management.

Findings and Results

In this study, grounded theory was employed to identify the variables affecting the reverse logistics supply chain for industrial waste management. As a qualitative approach, grounded theory enables the extraction of concepts and categories from raw data. The process of identifying variables was carried out in three main coding stages: open coding, axial coding, and selective coding.

1. Open Coding

In this stage, the raw data collected from semi-structured interviews with 17 academic and industry experts were examined line by line, and initial codes were extracted. Each meaningful sentence or phrase in the interviews was considered a code. For example, statements such as "the need to standardize waste management processes" or "the importance of employee training in reducing errors" were recorded as initial codes. Ultimately, more than 100 initial codes were extracted from the interviews.

2. Axial Coding

At this stage, the initial codes were grouped into subcategories based on conceptual similarity and thematic relationships. For instance, codes such as "process standardization," "operation scheduling," and "environmental laws and regulations" were grouped under the causal conditions subcategory. Similarly, codes such as "waste management," "specialized workforce," and "advanced technologies" were grouped under the core categories.

3. Selective Coding

In this stage, the subcategories were systematically organized into main categories. The six main categories identified included causal conditions, core categories, intervening/facilitating conditions, contextual conditions, strategies, and outcomes. Each main category was considered a key concept around which other subcategories were organized. For example, waste management was placed at the center of the model as the core category, while other categories such as causal conditions (e.g., standardization) and strategies (e.g., process digitalization) were connected to it.

Finally, through these stages, 25 subcomponents were identified within the six main categories. The list of subcomponents, their corresponding variables, and experts' opinions about each subcomponent are presented in the table below.

Table 1

List of Research Components

Main Categories	Component	Experts' Codes
Causal Conditions	Standardization	p1, p3, p6, p9, p13, p15, p16, p17
	Scheduling	p2, p4, p7, p8, p11, p10, p14
	Organizational Survival	p3, p5, p6, p12, p13
	Feedback and Learning	p1, p5, p6, p8, p11, p16, p17
	Laws and Regulations	p2, p6, p7, p9, p10, p13, p14
Core Categories	Waste Management	p1, p2, p3, p7, p13, p14
	Specialized Workforce	p7, p8, p11, p10, p12
	Technology	p5, p6, p8, p11, p12, p13, p17
	Communication	p9, p10, p13, p14, p15, p16, p17
Intervening/Facilitating Conditions	Training of Employees and Managers	p1, p2, p3, p5, p6, p7, p9, p10, p11, p13, p15, p16
	Infrastructure	p2, p3, p4, p5, p6, p7, p8, p9, p10, p11, p12
	Top Management Support	p4, p5, p6, p7, p8, p9, p10, p11, p16, p17
	Internal and External Environmental Conditions	p3, p7, p13, p14, p17
	Regulatory Bodies	p2, p3, p7, p13, p14, p15, p16, p17
Contextual Conditions	Organizational Culture	p1, p2, p3, p4, p5, p8, p11, p16, p17
	Organizational Structure	p4, p5, p6, p9, p13, p14
	Planning	p2, p3, p4, p5, p9, p12, p13
Strategies	Management and Process Digitalization	p2, p3, p4, p5, p9, p11, p13, p16
	Flexibility	p3, p5, p9, p13
	Alignment and Integration	p2, p3, p5, p10, p11
Outcomes	Cost Management	p1, p2, p3, p5, p6, p7, p9, p10, p11, p13, p15, p16
	Community Satisfaction	p1, p2, p3, p5, p6, p7, p9, p10, p11, p13, p15, p16, p17
	Environmental Pollution Reduction	p1, p2, p3, p4, p5, p6, p7, p8, p9, p10, p11, p12, p13, p14, p15, p16, p17
	Reduction in Raw Material Usage	p1, p2, p3, p4, p5, p6, p7, p8, p12, p13, p14, p15, p16, p17
	Risk Management	p1, p2, p3, p4, p5, p6, p7, p8, p9, p10, p11, p12, p15, p16, p17

System Dynamics

In this section, the findings derived from grounded theory were used to implement the system dynamics model of the reverse logistics supply chain for industrial waste management. After identifying the six main categories and 25 subcomponents, these variables were systematically presented in cause-and-effect diagrams to illustrate the complex relationships among them. Positive and negative feedback loops were identified, and the interactions of the variables were analyzed.

For example, an increase in waste management effectiveness leads to reduced environmental pollution and improved community satisfaction, while higher waste management costs may negatively affect organizational profitability. Subsequently, stock-and-flow diagrams were used to model state, rate, and auxiliary variables quantitatively, and their interrelationships were simulated using system dynamics software (Vensim).

These diagrams enabled dynamic analysis of the system and examined the impact of changes in key variables such as advanced technologies, top management support, and infrastructure on final outcomes, including pollution reduction and profitability improvement. Finally, by executing different scenarios, the system's behavior under various conditions was predicted, and practical solutions were proposed to improve industrial waste management.

Subsystems and Their Constituent Variables

In this section, the main subsystems of the reverse logistics supply chain model for industrial waste management are presented based on causal loop diagrams. These subsystems were designed using the variables identified through grounded theory and dynamically illustrate the complex relationships among factors influencing industrial waste management.

Each subsystem includes a set of variables interconnected through feedback loops. These loops are divided into two main categories: reinforcing (positive) loops and balancing (negative) loops.

Reinforcing Loops (Positive):

These loops strengthen the effects of variables and help the system grow in a particular direction. For example, increased waste management leads to reduced environmental pollution and greater community satisfaction, which in turn increases the demand for sustainable products and further reinforces waste management.

Balancing Loops (Negative):

These loops play a moderating role and guide the system toward equilibrium. For example, rising waste management costs may negatively affect organizational profitability, which in turn can reduce investment in waste management and consequently decrease waste management activities.

In these diagrams, the relationships between variables are indicated with positive (+) and negative (−) signs. A positive sign indicates a direct relationship (i.e., an increase in one variable leads to an increase in another), while a negative sign indicates an inverse relationship (i.e., an increase in one variable leads to a decrease in another). This analysis facilitates a better understanding of system behavior and helps identify leverage points for improving industrial waste management. Subsequently, each of these subsystems is examined in detail, and their constituent variables are described.

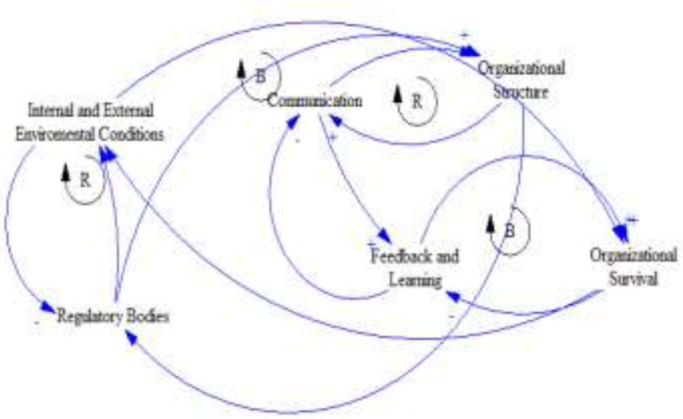
1. Drawing and Analyzing the Organizational and Environmental Subsystem

This subsystem examines the interactions between the organization's internal and external factors. As illustrated in Diagram (1), it includes the following key variables:

- Internal and external environmental conditions
- Regulatory bodies: external organizations and regulations that influence organizational performance
- Communication: information flow and internal and external interactions of the organization
- Organizational structure: the framework and internal organization that shape decision-making and strategy implementation
- Feedback and learning: processes that enable the organization to learn from past experiences and improve
- Organizational survival: the ultimate goal affected by the interactions among other variables

Figure 1

Causal Loop Diagram of the Organizational and Environmental Subsystem



This subsystem represents the complex interactions between internal and external factors that affect organizational survival and performance. Regulatory bodies may establish laws and regulations that influence organizational structure and communication. On the other hand, effective communication can enhance feedback and learning, which in turn improve organizational structure and adaptability to environmental changes. These positive and negative feedback loops ultimately impact organizational survival. Organizations that can effectively interact with regulatory agencies, build strong communication channels, and leverage feedback and learning for continuous improvement have a higher chance of survival and success in dynamic and competitive environments.

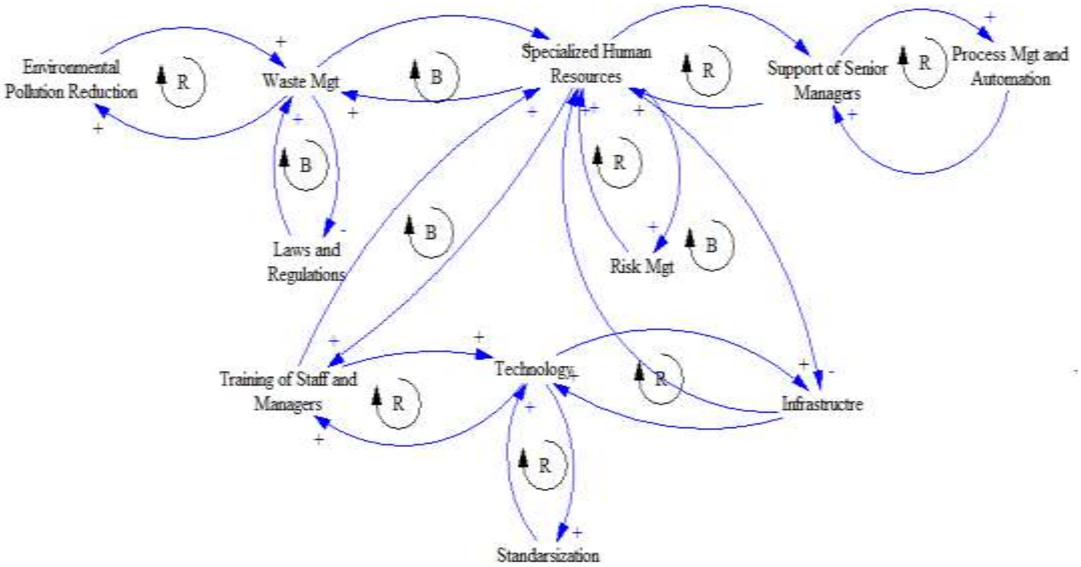
2. Drawing and Analyzing the Environmental Pollution Reduction Subsystem

This subsystem focuses on the factors and processes that contribute to reducing environmental pollution and includes the following key variables (Diagram (2)):

- Waste management: processes of waste collection, recycling, and disposal that help reduce pollution
- Laws and regulations: government directives and policies that require organizations to comply with environmental standards
- Employee and managerial training: educational programs that enhance awareness and skills necessary for implementing pollution reduction methods
- Technology: the use of advanced technologies to reduce pollution and improve processes
- Standardization: establishing and applying environmental standards to ensure process quality and sustainability
- Specialized human resources: trained and skilled personnel capable of implementing pollution reduction programs
- Top management support: the backing and commitment of senior leadership to environmental initiatives
- Process management and automation: optimizing processes and using automated systems to reduce errors and pollution

Figure 2

Causal Loop Diagram of the Environmental Pollution Reduction Subsystem



This subsystem shows the interactions among various factors involved in reducing environmental pollution. Waste management, as a key variable, directly affects pollution reduction. Environmental regulations create a framework for organizations to align their activities with environmental standards. Employee and managerial training enhance the awareness and ability to implement these standards. Technology and automation contribute to process improvement and pollution reduction. Top management support and the presence of specialized human resources ensure effective implementation of environmental programs. Finally, standardization guarantees that all processes are executed sustainably and with high quality. These complex interactions among variables form the foundation of an effective and sustainable pollution reduction system.

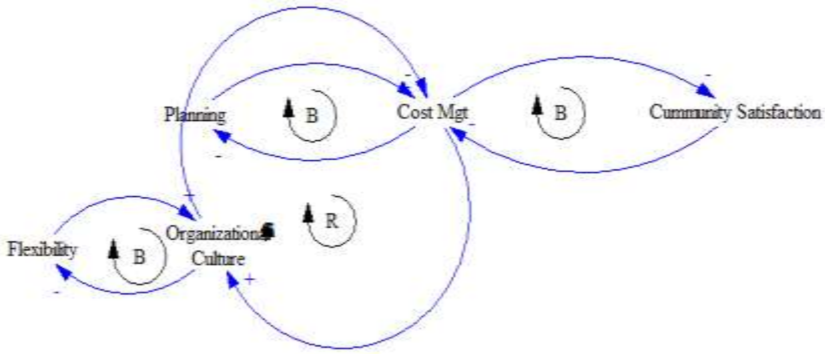
3. Drawing and Analyzing the Planning and Community Satisfaction Subsystem

This subsystem examines the factors and processes involved in planning and achieving community satisfaction and includes the following key variables (Diagram (3)):

- **Planning**: the processes of designing and implementing programs and projects.
- **Cost control**: managing and monitoring expenses to ensure the execution of projects within the allocated budget.
- **Community satisfaction**: the degree of approval and acceptance of executed projects and programs by the community.
- **Flexibility**: the organization’s ability to adapt to changes and new conditions.
- **Organizational culture**: the values, beliefs, and behaviors dominating the organization that affect how programs are implemented.

Figure 3

Causal Loop Diagram of the Planning and Community Satisfaction Subsystem



This subsystem illustrates the interactions among various factors that contribute to successful planning and the achievement of community satisfaction. Effective planning helps the organization clearly define its objectives and allocate resources appropriately. Cost control ensures that projects are executed within the allocated budget and prevents resource waste. Community satisfaction, as a key indicator, reflects the success of projects and programs from the perspective of external stakeholders. Flexibility enables the organization to respond quickly to unforeseen changes and challenges. Organizational culture plays an essential role in how programs are implemented and how the organization engages with the community. A strong and positive organizational culture can improve internal collaboration and increase community satisfaction. These complex interactions among variables form the foundation of an efficient and successful planning system.

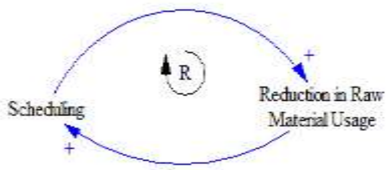
4. Drawing and Analyzing the Scheduling and Raw Material Consumption Reduction Subsystem

This subsystem examines the factors and processes involved in managing scheduling and reducing raw material consumption and includes the following key variables (Diagram (4)):

- **Scheduling**: planning and managing time for the execution of projects or processes.
- **Reduction of raw material consumption**: actions aimed at optimizing and decreasing the use of raw materials in processes.

Figure 4

Causal Loop Diagram of the Scheduling and Raw Material Consumption Reduction Subsystem



This subsystem illustrates the interaction between two key factors that play an important role in the efficiency and sustainability of processes. Effective scheduling helps the organization execute projects and processes on time and with high efficiency. This not only saves time but can also contribute to cost reduction. On the other hand, reducing raw material consumption leads to resource optimization and waste reduction, which are economically and environmentally significant. Lower raw material consumption can reduce production costs and alleviate pressure on natural resources.

The interaction between these two variables can improve process efficiency and sustainability. For example, precise scheduling can help the organization use raw materials more effectively and prevent resource waste. Ultimately, this subsystem helps the organization achieve both its economic and environmental goals.

Stock and Flow Diagrams

Stock-and-flow diagrams are essential tools in system dynamics that help us model the structure of a system dynamically and comprehensively. These diagrams categorize variables into two main types: Stocks and Flows, allowing us to understand how the system evolves over time.

Stocks represent resources or accumulations that change over time (such as raw material inventory or pollution levels), while Flows represent the rates of change in these stocks (such as production rate or pollution reduction rate). Additionally, Auxiliary Variables act as mediating or influencing factors that impact flows. These variables may include internal and external factors that affect system behavior.

Next, the identified variables are classified into three categories: stocks, flows, and auxiliary variables. Stocks represent resources or accumulations that change over time and indicate the system's state at any given moment. Flows determine the rate of change of these stocks and represent the inputs and outputs of the system. Auxiliary variables serve as intermediaries that influence flows and act as supportive factors within the system.

This classification helps analyze the system's structure more accurately and in a more organized way.

1. Stocks

Stocks are variables that change over time and represent the resources or inventories of the system. These variables include the following:

- **Organizational survival**: the ability of the organization to continue existing and operating in the long term.
- **Community satisfaction**: the level of satisfaction of external stakeholders with the organization's performance.
- **Environmental pollution level**: the amount of pollution generated by the organization.
- **Cost management**: the level of organizational expenses and how they are controlled.
- **Risk management**: the level of identified and managed risks within the organization.

2. Flows

Flows represent the rates of change in the stocks and are usually connected to stocks as inputs or outputs. These variables include the following:

- **Pollution reduction rate**: the speed of reducing environmental pollution.
- **Raw material consumption rate**: the speed of using raw materials in production processes.
- **Community satisfaction improvement rate**: the speed of increasing community satisfaction with the organization's performance.
- **Learning and feedback rate**: the speed of process improvement through feedback and learning.
- **Cost reduction rate**: the speed of reducing organizational costs.
- **Risk management rate**: the speed of identifying and mitigating risks.

3. Auxiliary Variables

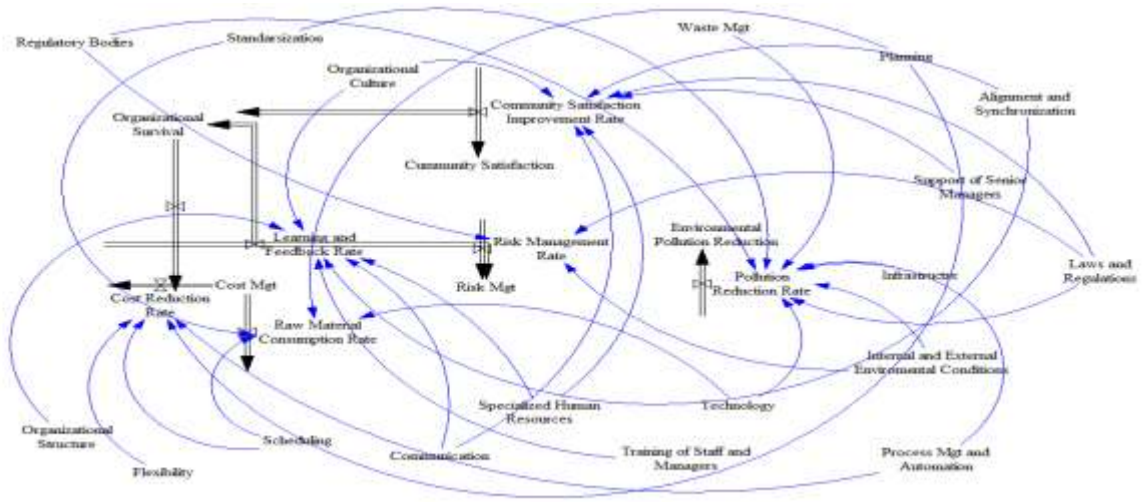
Auxiliary variables are mediating factors that influence flows and act as supportive elements within the system. These variables include the following:

- **Standardization**: influences the pollution reduction rate and raw material consumption rate.
- **Scheduling**: influences the raw material consumption rate and cost reduction rate.
- **Waste management**: influences the pollution reduction rate.
- **Specialized human resources**: influence the learning and feedback rate and the community satisfaction improvement rate.
- **Technology**: influences the raw material consumption rate and pollution reduction rate.
- **Communication**: influences the community satisfaction improvement rate and the learning and feedback rate.
- **Employee and managerial training**: influences the learning and feedback rate.
- **Infrastructure**: influences the pollution reduction rate.
- **Top management support**: influences the community satisfaction improvement rate and the learning and feedback rate.
- **Internal and external environmental conditions**: influence the pollution reduction rate and the risk management rate.
- **Regulatory bodies**: influence the pollution reduction rate and the risk management rate.
- **Organizational culture**: influences the community satisfaction improvement rate and the learning and feedback rate.
- **Organizational structure**: influences the learning and feedback rate.
- **Planning**: influences the raw material consumption rate and cost reduction rate.
- **Process management and digitalization**: influence the cost reduction rate and pollution reduction rate.
- **Economic feasibility**: influences the cost reduction rate.
- **Alignment and integration**: influence the community satisfaction improvement rate and the learning and feedback rate.
- **Laws and regulations**: influence the pollution reduction rate, the risk management rate, and the community satisfaction improvement rate.

After defining the stock, flow, and auxiliary variables in Vensim software and generating the stock-and-flow diagram, the graph representing the stock-and-flow model is shown in Diagram (5).

Figure 5

Conceptual Model of the Research as a Stock-and-Flow Diagram



This system dynamics model, designed using a stock-and-flow diagram, examines the interactions among key factors in the reverse logistics supply chain management for industrial waste in the gas refining industry. In this model, stocks represent the resources or inventories of the system, while flows show the rates of change in these stocks. Auxiliary variables act as mediating factors influencing the flows.

This model specifically focuses on the role of laws and regulations, organizational culture, and community satisfaction, demonstrating how these elements can influence industrial waste management.

In this model, community satisfaction is considered a key stock affected by the community satisfaction improvement rate. This flow, in turn, is influenced by auxiliary variables such as laws and regulations, organizational culture, and organizational structure. Stricter laws and regulations can increase community satisfaction by improving organizational performance in waste management. Additionally, a strong organizational culture and a flexible organizational structure can enhance internal and external communication, thereby improving community satisfaction. These interactions highlight the importance of aligning internal and external factors to achieve waste management goals.

Moreover, environmental pollution reduction is another key stock in this model and is influenced by the pollution reduction rate. This flow is affected by auxiliary variables such as laws and regulations, standardization, and technology. Regulations can push organizations toward adopting advanced technologies to reduce pollution by enforcing stricter environmental standards. Standardization can also improve waste management processes and thus increase the pollution reduction rate. This model shows how the interaction of legal, technological, and organizational factors can lead to environmental pollution reduction and overall improvement in the waste management system's performance.

Finally, this system dynamics model demonstrates that effective reverse logistics supply chain management in the gas refining industry requires simultaneous attention to internal and external factors. Laws and regulations, organizational culture, and community satisfaction serve as key elements that can significantly affect organizational performance in waste management. By improving these factors, organizations can achieve not only their environmental goals but also enhance community satisfaction and ensure long-term organizational survival. This model, as a powerful analytical tool, can support decision-makers in designing and implementing more effective policies and strategies for managing industrial waste.

Model Validation

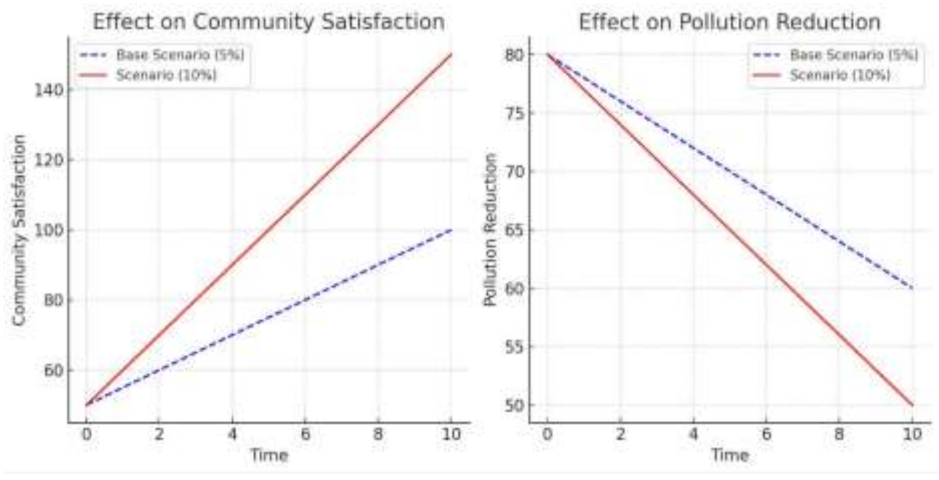
In the process of developing and evaluating reverse logistics supply chain management models, model validation is of great importance to ensure that the model can accurately simulate real-world conditions and predict system behavior in an operational environment. For this purpose, sensitivity analysis is used as a powerful tool to examine the impact of changes in key model parameters on outputs. This analysis not only helps identify influential factors affecting the system but also confirms the model's validity by comparing simulation results with real data or hypothetical scenarios. In this study, sensitivity analysis was applied to validate the industrial waste management model for Iran's gas refining industry to ensure that the model accurately reflects system behavior under various conditions and can be used as a reliable tool for strategic decision-making.

Sensitivity Analysis Test (Scenario One)

Sensitivity analysis and model validation are among the critical steps in evaluating reverse logistics supply chain management models, aimed at examining the effect of changes in key parameters on the overall system performance. This analysis helps identify influential factors and provides a deeper understanding of the model's behavior under different conditions. In this study, focusing on the industrial waste management model for Iran's gas refining industry, two different scenarios were examined, including changes in the community satisfaction improvement rate and organizational environmental pollution reduction. The objective of this analysis was to assess the model's sensitivity to changes in these parameters and verify the validity of the model results under real-world conditions, thereby enabling the design of more effective strategies to improve supply chain performance.

Figure 6

Sensitivity Analysis Based on the Scenario of Increasing the Community Satisfaction Improvement Rate



The above diagrams show the effect of increasing the community satisfaction improvement rate from 5% to 10%:

In the left diagram, increasing the rate of community satisfaction improvement results in greater growth of community satisfaction over time (red line). In the baseline scenario (blue line), this growth is slower.

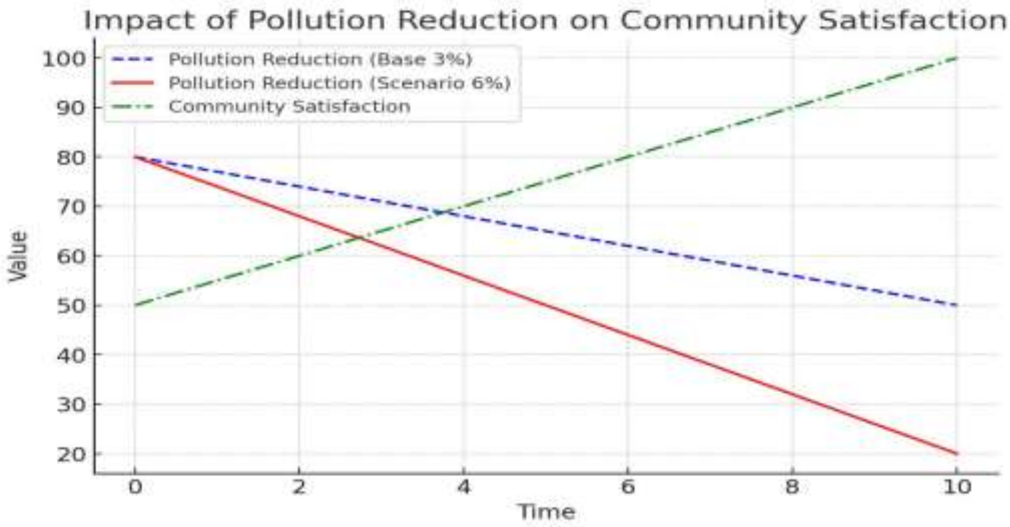
In the right diagram, increasing community satisfaction leads to a reduction in environmental pollution; however, in the new scenario (red line), this reduction is stronger. In the baseline scenario (blue line), the pollution reduction trend is slower. This analysis demonstrates that increasing the community satisfaction improvement rate has a positive impact on reducing environmental pollution.

Sensitivity Analysis Test (Scenario Two)

In this stage, the second scenario, which involves changes in organizational environmental pollution reduction, is analyzed by examining the impact of increasing the pollution reduction rate from 3% to 6%.

Figure 7

Sensitivity Analysis Based on the Scenario of Increasing the Environmental Pollution Reduction Rate



In this diagram, the blue dashed line represents pollution reduction in the baseline scenario (3% reduction per time unit). The red solid line shows pollution reduction in the new scenario (6% reduction per time unit). The green dotted line indicates the increase in community satisfaction, which improves over time due to pollution reduction. This analysis shows that increasing the pollution reduction rate (6% instead of 3%) leads to faster pollution reduction and, consequently, increased community satisfaction.

Discussion and Conclusion

The present study aimed to design and validate a dynamic system model for reverse logistics (RL) supply chain management in the gas refining industry with a focus on improving industrial waste management by integrating environmental, economic, and social dimensions. The results revealed that the proposed model successfully captured the complex, multi-level interactions among key drivers of RL performance, including regulatory enforcement, technological capability, infrastructure development, organizational culture, cost optimization, and community satisfaction. Sensitivity analysis confirmed the model's ability to simulate realistic system behavior, demonstrating that enhancing the rate of community satisfaction improvement significantly accelerates environmental pollution reduction, while increasing the pollution reduction rate itself leads to faster environmental improvement and reinforces social acceptance. These findings indicate that dynamic modeling can provide actionable insights for balancing ecological outcomes, operational costs, and stakeholder expectations in highly sensitive industrial environments.

The first critical finding is the central role of regulatory frameworks and environmental governance in shaping RL system performance. By simulating scenarios with stricter regulatory enforcement, the model showed measurable improvements in pollution reduction and community satisfaction, aligning with prior work emphasizing regulatory pressure as a key driver of RL adoption [19, 20]. Studies in related heavy industries have also identified compliance requirements and environmental standards as critical motivators for developing RL networks [21, 22]. Our results further confirm that regulations not only trigger initial RL adoption but also sustain continuous improvement by encouraging investment in advanced technologies and process standardization [23, 24]. The positive influence of regulatory tightening on social perception found here is consistent with the insights of Alsaif et al. [25], who showed that stricter compliance in petrochemical supply chains fosters corporate legitimacy and social license to operate.

Another key outcome concerns the role of technology and process digitalization in enhancing both environmental and economic performance. The model indicates that increased adoption of advanced technologies, including automated process control and waste tracking, reduces raw material consumption and accelerates pollution reduction. These results support findings by Kakouei et al. [26], who proposed optimization models to minimize environmental impact, and by Eslampanah et al. [27], who demonstrated that technology-enabled networks improve waste collection efficiency and reduce system costs. Likewise, the integration of digital infrastructure and intelligent networks (such as VANET-based waste transport optimization) strengthens decision-making capacity and real-time adaptability [28, 29]. Gao et al. [30] similarly observed that digital eco-label and IoT solutions improve operational control and drive competitiveness in green supply chains. The current findings add to this literature by showing how technological advancement interacts dynamically with other factors, such as top management support and organizational culture, to yield sustained system-wide benefits.

The results also underscore the pivotal role of organizational culture, learning, and feedback loops in supporting RL success. The model demonstrates that strong internal communication, a culture of adaptability, and structured feedback mechanisms amplify the effectiveness of regulatory policies and technological upgrades. This aligns with the conceptual and empirical work of Mohammadpour [31], who emphasized the philosophical and methodological need for reflective, learning-oriented systems in complex industrial management. It also corroborates findings by Mahmoudi [32], showing that cultural readiness and employee engagement mitigate resistance to RL implementation. Furthermore, top management support emerged as a critical enabler, reinforcing previous research that links executive commitment to higher investment in green practices and infrastructure [33, 34]. The integration of cultural and leadership variables within a dynamic systems model is a novel contribution of this study, advancing beyond static frameworks to capture the feedback-driven nature of behavioral and organizational change.

Another important result is the confirmation of community satisfaction as both an outcome and a driver of RL sustainability. The analysis showed that improving waste management performance feeds back into higher public trust and acceptance, which in turn motivates continued investment and policy support. This reciprocal relationship is consistent with findings in sustainability and supply chain governance research [24, 25]. For industries with high environmental exposure such as gas refining, social legitimacy is increasingly linked to operational resilience and cost predictability [35, 36]. By explicitly modeling community satisfaction as a stock influenced by internal (organizational culture, communication) and external (laws, regulations) variables, this research extends previous models that have typically treated social dimensions as secondary performance indicators [37, 38].

The study further confirms the interdependence of cost management and environmental performance. Dynamic simulation showed that while stricter environmental initiatives may initially increase costs, long-term benefits include resource optimization and risk reduction, leading to improved financial sustainability. These findings echo those of Feizollahi and Heydari [39], who developed multi-objective CLSC models balancing cost and environmental performance under uncertainty, and are supported by Tavakoli et al. [40], who demonstrated that integrated forward-reverse networks in energy projects enhance overall profitability despite short-term cost pressures. Additionally, the alignment of forward and reverse logistics flows, as highlighted in our results, resonates with the coordination-based frameworks of Gao et al. [30] and the postponement strategies suggested by Rau et al. [41] for coping with demand uncertainty.

From a methodological standpoint, the successful application of system dynamics combined with grounded theory confirms the suitability of this hybrid approach for complex sustainability challenges. The study began with qualitative identification of key RL variables through expert interviews, consistent with approaches recommended by Najm and Asadi Gangraj [42] in designing RL networks under local constraints. These qualitative insights were then transformed into a quantitative dynamic model that can test policy and operational scenarios, as advocated by Elmi et al. [43] and Eslampanah et al. [27]. This integration bridges a methodological gap in the field, which has often relied on static optimization or descriptive frameworks unable to capture non-linear, time-dependent interactions [31, 34].

The validation of the model using sensitivity analysis strengthens its practical relevance. Testing the effect of increased community satisfaction improvement rates and enhanced pollution reduction rates confirmed the model's ability to anticipate system response under different strategic interventions. This approach parallels the validation strategies seen in Kakouei et al. [26] and Yu et al. [23], where scenario-based analyses validated RL design decisions under uncertainty and stress conditions. By demonstrating how small parameter adjustments—such as increasing public engagement efforts or accelerating pollution control initiatives—can generate system-wide benefits, this study contributes actionable insights for managers seeking evidence-based policies.

Overall, the findings of this research align with and expand existing literature on sustainable RL and CLSC design. They highlight the necessity of viewing waste management in the gas refining industry as a dynamic, interconnected system where technical, regulatory, economic, and social factors co-evolve. They also confirm that advanced dynamic modeling can move RL research from conceptual discussions and static optimization to predictive, adaptive decision-support tools.

Despite its contributions, the study has several limitations. First, while the dynamic model was constructed using extensive expert input from the gas refining industry, the sample size of experts was limited and focused on one national context, which may reduce generalizability. The specific regulatory, cultural, and infrastructural conditions of the Iranian gas refining sector could differ significantly from other regions, limiting cross-industry and cross-country applicability. Second, although system dynamics provides powerful tools for capturing complex feedback structures, it inherently requires simplifying assumptions, such as aggregated variable definitions and fixed functional relationships, which may oversimplify real-world uncertainties. Third, the model was validated primarily through sensitivity analysis and theoretical scenario testing rather than large-scale real-world implementation, which may limit its predictive accuracy when exposed to unforeseen shocks such as global supply chain disruptions or extreme environmental events. Finally, the model emphasizes macro-level system factors and may not fully capture firm-level micro-dynamics such as workforce behavior, interdepartmental conflicts, and supplier heterogeneity.

Future research should focus on extending the model across different industrial and geographic contexts to test its robustness under diverse regulatory frameworks and market dynamics. Comparative studies across multiple countries or sectors, such as petrochemicals, mining, and construction, could help refine the generalizability of the dynamic RL approach. There is also a need to integrate advanced data analytics and real-time monitoring technologies, such as IoT sensors and machine learning prediction, into system dynamics models to better capture uncertainty and dynamic risk management.

Incorporating behavioral modeling, including stakeholder trust dynamics and organizational change resistance, could further enhance the model's accuracy in representing social and cultural variables. Finally, longitudinal empirical validation using real operational data from RL implementation projects would strengthen confidence in the model's predictive power and provide actionable feedback for refining system assumptions.

Practitioners in the gas refining and similar heavy industries can apply the validated model as a decision-support tool to plan and monitor sustainable waste management strategies. Managers should focus on aligning regulatory compliance with proactive technological investment, using digital systems and process automation to optimize reverse flows. Building a strong organizational culture that promotes learning, communication, and environmental accountability can amplify the effectiveness of policy and technological changes. Engaging communities early and transparently can enhance social acceptance and reduce risk of resistance, while scenario testing using the dynamic model can help organizations anticipate cost and environmental trade-offs before implementing new waste management policies or infrastructures.

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Authors' Contributions

All authors equally contributed to this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

The study protocol adhered to the principles outlined in the Helsinki Declaration, which provides guidelines for ethical research involving human participants. Written consent was obtained from all participants in the study.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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