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Presenting a Technology Diffusion Model in Iran's Petro-Refinery Sector Using the System Dynamics Approach

Mansoureh. Esmaeili[1], Mohammad Mehdi. Movahhedi[2], Majid. Motamedi[3*]

[1] Department of Technology Management, KI.C., Islamic Azad University, Kish, Iran
[2] Department of Industrial Management, SR. C., Islamic Azad University, Tehran, Iran
[3] Department of Industrial Management, Nos.C., Islamic Azad University, Noshahr, Iran

*** Corresponding author email address**: majidmotamedi@iau.ac.ir

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A B S T R A C T

This article employs the system dynamics approach to examine and analyze the process of technology diffusion in Iran’s petro-refinery industry. Initially, key factors influencing technology diffusion were identified, including: technology development organizations and managerial infrastructure, needs assessment and feasibility studies, negotiation and contract finalization skills, training and technology transfer, industrial implementation, feedback and continuous improvement, international collaborations and sanctions, diffusion costs, and delays in contract execution. Subsequently, using system dynamics modeling, the causal relationships among these factors and their mutual impacts on the process of technology diffusion in the petro-refinery sector were analyzed. Finally, the current state of this industry regarding technology diffusion was simulated. The projection indicates that, under the existing trajectory, it would take centuries for all transferred technologies to reach the diffusion stage—unless reforms are implemented in the process, such as increasing the number of technology development organizations and managerial infrastructures, and ensuring oversight and control by these organizations throughout all stages of technology transfer.

Keywords: *Technology diffusion, Causal loop diagrams, Petro-refinery.*

1. Introduction

In the increasingly competitive and innovation-driven global economy, technology transfer has emerged as a strategic mechanism for industrial modernization and sustainable development. Particularly in complex and resource-intensive sectors such as the petro-refining industry, the ability to absorb, localize, and diffuse advanced technologies plays a crucial role in enhancing productivity, reducing environmental impact, and strengthening national technological sovereignty. The Iranian petro-refining sector, which lies at the heart of the country’s energy economy, has encountered multiple structural, geopolitical, and organizational challenges in adopting and effectively diffusing imported technologies. These include sanctions-induced constraints, infrastructural inefficiencies, weak linkages between knowledge-generating institutions and industry, and limited investment in systematized technology management. Addressing these challenges necessitates a comprehensive and dynamic framework capable of identifying and simulating the interrelationships among key drivers and barriers of technology diffusion. System dynamics modeling provides such a tool, allowing policymakers and industrial stakeholders to visualize the feedback loops, time delays, and causal relationships inherent in the technology transfer process (Esmaeili et al., 2025).

Technology transfer, broadly defined as the systematic transmission of technical knowledge, skills, processes, and innovations from one entity to another, often spans institutional boundaries such as firms, universities, and governments (Hayter et al., 2023). The success of this process is heavily dependent on the absorptive capacity of the recipient, the compatibility of the transferred technology with local needs and contexts, and the strategic alignment of technology transfer objectives with long-term development goals (Ren et al., 2023). In the context of Iran's petro-refining industry, which aims to reduce dependency on crude oil exports and shift toward value-added production, successful technology diffusion could enable the sector to bridge the technological gap with global leaders, improve energy efficiency, and meet international environmental standards (Hajiebrahimi Farashah et al., 2020). However, the current literature underscores that many technology transfer efforts fail to progress beyond the initial stages of acquisition and pilot testing due to a lack of integrated planning, feedback mechanisms, and coordination among key stakeholders (Barros et al., 2020; Radfar & Khamseh, 2021).

Previous studies have explored technology transfer processes in various industrial settings. For instance, (Sikdar & Mukhopadhyay, 2020) identified a strong linkage between technology transfer and productivity growth in Indian manufacturing industries, attributing success to industry-wide learning and investment in absorptive capacities. (Zhenxu et al., 2024) used system dynamics modeling to evaluate the implementation effectiveness of technology transfer policies in China's Liaoning province, highlighting the importance of policy design, institutional support, and dynamic feedback in sustaining long-term diffusion. Similarly, (Sadeghi et al., 2022) employed system dynamics to explore capacity constraints in Iran's polymer pipe and fittings industry, emphasizing the need for aligning technological investments with infrastructure and training. These studies collectively affirm that technology transfer is not a linear or static event but a continuous and adaptive process that benefits from systemic modeling approaches.

In recent years, the development of dynamic models to simulate technology diffusion processes has gained traction in strategic management and innovation literature. These models enable researchers and practitioners to capture the nonlinear behavior of complex systems and to test various policy scenarios under conditions of uncertainty and feedback. (Motamedi & Darvish Motavalli, 2025) emphasized that structural validation is a prerequisite for behavior testing in system dynamics, reinforcing the need to ensure internal consistency within causal feedback loops. This methodology is particularly relevant in sectors like petro-refining, where multiple actors—including state-owned enterprises, regulatory agencies, R&D institutions, and foreign licensors—interact within a highly regulated and technologically intensive environment (Khamseh, 2023).

To operationalize technology transfer in such environments, several critical components must be taken into account. First is the alignment between technology supply and demand, which includes the identification of technological needs, feasibility assessment, and market readiness. Second is the design of appropriate institutional and infrastructural mechanisms to facilitate the absorption and customization of imported technologies. According to (Lima, 2004), effective university-industry cooperation frameworks play a pivotal role in enabling this transition by fostering shared research, joint ventures, and knowledge co-production. Third is the integration of performance monitoring, feedback loops, and continuous improvement mechanisms to sustain and evolve technological capabilities post-transfer (Artyukhov et al., 2023; Barros et al., 2020).

Moreover, the global innovation transfer landscape is rapidly evolving due to digital transformation, decentralized innovation ecosystems, and the shift toward sustainability-oriented business models. The SPACE-RL model introduced by (Bilan et al., 2023) and further elaborated by (Artyukhov et al., 2023) emphasizes the need for feedback-driven, resilient learning systems that bridge the "science–business" gap and promote institutional collaboration. In the Iranian context, applying such models requires careful consideration of national constraints, including sanctions, limited foreign investment, and underdeveloped knowledge infrastructure (Jalilzadeh Tabrizi & Jalalpour, 2023).

Despite these challenges, recent efforts to improve technology transfer frameworks in Iran's petro-refining sector have yielded promising outcomes. For example, (Esmaeili et al., 2025) developed a system dynamics model that maps the causal relationships between strategic variables such as training, negotiation skills, institutional support, and technological localization. Their findings demonstrate that enhancing the role of technology development organizations, fostering university-industry linkages, and ensuring continuous feedback loops significantly improve diffusion outcomes. These insights align with broader theoretical perspectives that stress the importance of absorptive capacity and structural capital in determining the success of technology transfer efforts (Barge-Gil & Lo'pez, 2014; Hamilton & Philbin, 2020).

Furthermore, scholars such as (Mykytyuk & Kasych, 2020) argue that innovation systems in infrastructure-heavy industries must adopt adaptive mechanisms to manage the lifecycle of transferred technologies—from acquisition to deployment and eventual upgrading. This is particularly relevant in petro-refining, where technological systems are capital-intensive and require long-term planning and multi-stakeholder cooperation. In this context, applying a system dynamics framework allows for a holistic examination of interdependencies across organizational, technical, and policy dimensions (Motamedi & Darvish Motavalli, 2025; Zhenxu et al., 2024).

The present study builds upon this growing body of literature by developing and validating a system dynamics model tailored to the specific characteristics of Iran's petro-refining industry. The model identifies key reinforcing and balancing loops that govern technology diffusion, such as the role of feedback and continuous improvement, the effects of international sanctions, the need for customized training programs, and the importance of strategic negotiations and contract management. The integration of structural validation, extreme condition testing, and boundary adequacy assessments—drawing from the methods of (Motamedi & Darvish Motavalli, 2025)—ensures that the model is both theoretically grounded and practically applicable.

In sum, this research aims to offer a comprehensive and empirically supported framework for understanding and enhancing the technology diffusion process in Iran's petro-refining sector.

2. Methods and Materials

Given that data in this research were collected from managers and experts in petro-refinery companies, the study is categorized as applied and descriptive-survey research. The applied methodology is illustrated in Figure 2. This approach begins with an analysis of the petro-refinery industry in Iran, where strategic issues within the sector are examined. A review of the literature revealed that the most critical strategic challenge—identified as the key development bottleneck—is technology transfer.

Subsequently, based on library studies, internal variables and dynamics within each loop were identified. In the next stage, industry experts were purposively selected according to the criterion that these individuals must possess both advanced academic and managerial knowledge, along with practical experience in technology transfer projects within petro-refineries, and a willingness and availability to participate in the study. Ultimately, 10 individuals were selected for final inclusion, all with 18 to 36 years of experience and holding at least a master's degree.

In the following stages, the identified variables and the causal loop diagram were evaluated using a questionnaire based on the diagram and semi-structured interviews, continuing until expert consensus was achieved. The final model was then tested using a structural consistency test and validated by the experts. It was ultimately employed for drawing conclusions and providing improvement recommendations.

It should be noted that a systemic approach was applied in this study using the Vensim software.

3. Findings and Results

Given that the diffusion phase is the final and one of the most critical stages in the technology transfer process—during which the absorbed technology is broadly utilized across the organization and nationally—this stage requires advanced managerial and organizational infrastructures to ensure the stabilization and deepening of technical knowledge, standardization, and continuous improvement. Therefore, in Figure 1, which presents the causal loop diagram of technology diffusion in petro-refineries, the reinforcing loop R1 indicates that the initiation of technology diffusion originates from the technology development organization.

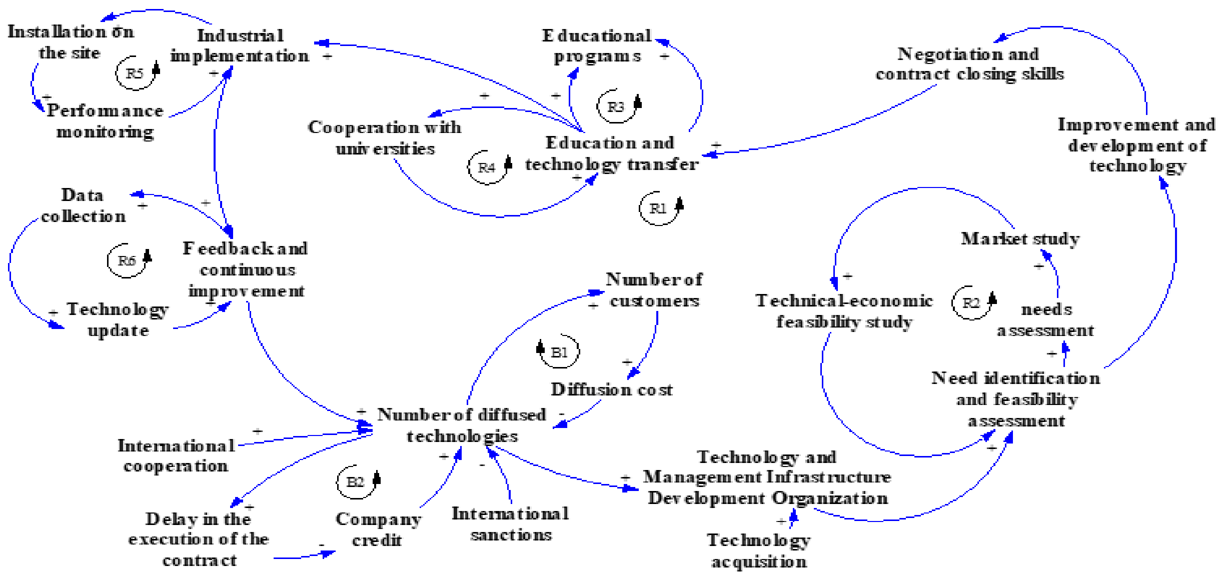
The Role of the Technology Development Organization in Technology Diffusion

- **Coordination and Facilitation of Technology Diffusion:** The technology development organization, as the central authority, steers the transfer of knowledge and technology from laboratory or pilot scale to industrial and operational levels. By establishing clear frameworks, the organization prevents error repetition and resource wastage, thereby systematizing the diffusion process.

- **Creation and Strengthening of Structural Capital:** Successful technology transfer in the petrochemical and petro-refinery sectors requires robust structural capital. This includes supportive systems and methods, knowledge management infrastructure, a supportive organizational culture, and an appropriate organizational structure. The presence of the technology development organization enhances and integrates these components to ensure technology is effectively diffused throughout the organization and the industry.
- **Development and Management of Organizational Knowledge:** During the diffusion phase, it is essential to document and share acquired technical knowledge and experiences. The technology development organization enables the transfer of tacit knowledge and experience by establishing knowledge management infrastructures and databases, thus preventing knowledge loss and redundancy.
- **Ensuring Continuous Improvement and Up-to-Date Practices:** As technologies evolve rapidly, the technology development organization monitors global advancements and continuously upgrades infrastructures to avoid technological obsolescence and foster ongoing improvement.

Figure 1

Causal Loop Diagram of Technology Diffusion



Importance of Managerial Infrastructures

- **Data Integration and Data-Driven Decision-Making:** Modern managerial infrastructures enable the collection, analysis, and utilization of operational data. In petro-refineries—where massive volumes of operational data are generated—such capabilities are crucial for process optimization and productivity enhancement.
- **Increased Efficiency and Cost Reduction:** With the implementation of advanced management systems (such as IoT, digital platforms, and big data analytics), real-time monitoring, energy consumption optimization, waste reduction, and equipment longevity are achievable, all of which directly impact profitability and sustainability.
- **Enhanced Safety and Risk Management:** Smart digital managerial infrastructures, using sensors and monitoring systems, mitigate operational risks and ensure the safety of personnel and equipment.

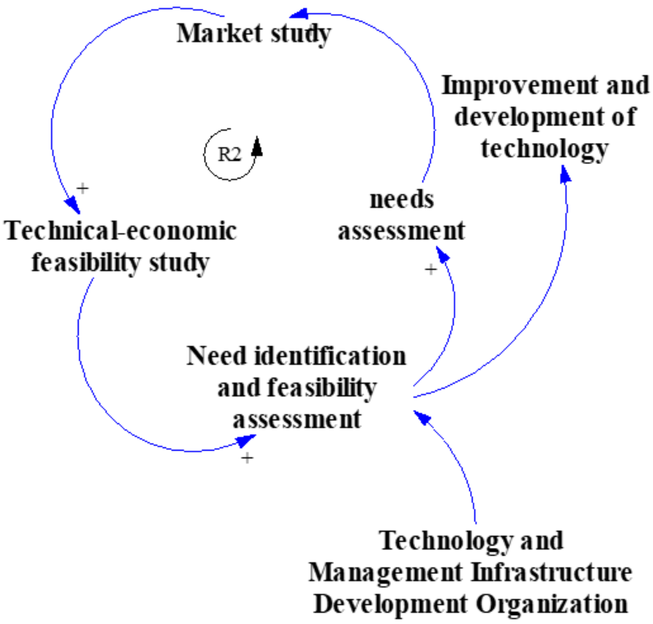
Thus, during the technology diffusion stage, the presence of a technology development organization and advanced managerial infrastructures is a prerequisite for full utilization of new technologies, knowledge integration, productivity enhancement, and maintaining competitive advantage in Iran's petro-refineries. Without these structures, the absorbed technologies will not be properly institutionalized within the organization, and the anticipated benefits will not materialize.

Needs Assessment and Feasibility Study

Needs identification and feasibility studies are among the most essential and critical steps in the technology transfer and diffusion process within the petro-refinery industry. This reinforcing loop is represented by R2 in the causal loop diagram of technology diffusion (Figure 2).

Figure 2

Reinforcing Loop R2 in Technology Diffusion



The necessity of this process is explained by the following reasons:

- **Aligning Technology with the Real Needs of the Industry:** Accurate identification of technological needs ensures that the selected technology truly addresses the operational, environmental, and economic challenges and priorities of petro-refineries, thereby preventing the adoption of inefficient or irrelevant technologies.
- **Reducing Investment Risk and Improving Effectiveness:** Feasibility studies evaluate technical, economic, market, environmental, and infrastructural dimensions of the project, preventing resource waste, construction of inefficient units, low-value-added products, and environmental issues, and paving the way for sustainable development.
- **Selecting Suitable Technology and Optimizing Processes:** Feasibility assessments help in choosing technologies compatible with local conditions, feedstock availability, target markets, geographic location, and existing capacities. For example, conversion processes should be selected based on site location, market needs, and environmental requirements to ensure maximum profitability and minimal harm.
- **Enhancing Value-Added and Competitiveness:** Through accurate needs assessment and feasibility studies, petro-refineries can produce strategic and in-demand products with higher value-added, strengthening Iran's competitive position in regional and global markets.
- **Preventing Redundancy and Resource Waste:** Feasibility studies refine projects technically and economically, filtering out unfeasible or unjustifiable projects. If a project is deemed unfeasible, it is terminated early and resources are redirected to better alternatives.

Therefore, based on the required expertise, the identification of technological needs and their feasibility is conducted through market research and economic evaluations within the technology development organization and managerial infrastructures.

Negotiation and Contracting Skills in the Technology Diffusion Process in Iran's Petro-Refineries

The necessity of effective negotiation and contracting skills in the technology diffusion process in Iran's petro-refineries is critical for the following reasons:

- **Addressing Challenges from Sanctions and International Constraints:** Due to sanctions, Iran often faces obstacles such as limited access to technology vendors, restrictions on knowledge transfer, or issues with international payments. Negotiation skills enable alternative solutions—like engaging reputable intermediaries, barter contracts, or attracting third-party partners—to overcome such barriers.
- **Protection of Intellectual Property:** Weak contracts may endanger intellectual property protection and halt technology diffusion. Without such protection, the incentive for innovation declines, investments diminish, and technological progress is compromised. Robust legal frameworks not only safeguard creators' rights but also support the growth of the knowledge-based economy and balance global markets.
- **Securing Mutual Interests and Building Trust for Future Cooperation:** One-sided or coercive negotiations (e.g., pushing for low pricing without considering vendor interests) may result in project failure or reduced post-sale support quality. Skillful negotiations that aim for win–win agreements pave the way for future advanced technology transfers. For instance, co-developing new technologies could be proposed as a condition for reducing transfer costs.
- **Compliance with Domestic and International Legal Requirements:** Contracts must align with Iran's domestic laws (such as FATF accession or environmental regulations) and international provisions (like export control treaties) to avoid project cancellations due to legal violations.
- **Flexibility in the Face of Unforeseen Changes:** In the oil industry—subject to global price fluctuations, political shifts, or crises like pandemics—contracts must include adaptive clauses (e.g., price revisions based on energy indices) or safe exit mechanisms. For example, contracts could stipulate cost adjustment mechanisms based on global crude oil prices.

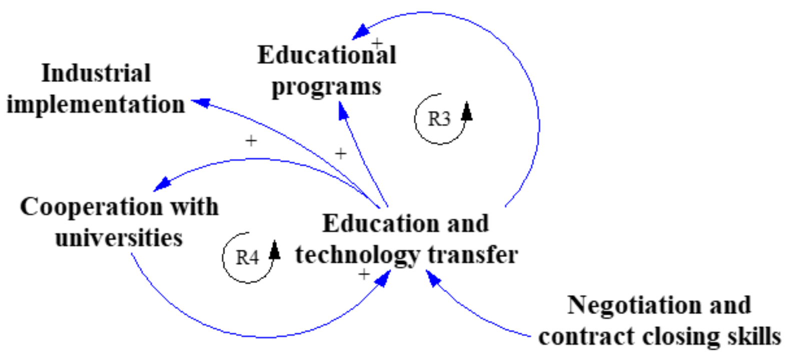
Thus, negotiation and contracting skills form one of the most vital components in the technology diffusion loop, reinforcing loop R1. Without these skills, even the most advanced technologies may never be effectively operationalized due to executive or legal barriers.

Training and Technology Transfer

Training and technology transfer through educational programs and university collaborations play a crucial role in facilitating and accelerating the technology transfer process in Iran's petro-refineries. The reinforcing role of educational programs and university cooperation in technology diffusion is illustrated in reinforcing loops R3 and R4 in Figure 3.

Figure 3

Reinforcing Loops R3 and R4 in Technology Diffusion



The impact of training and technology transfer on diffusion can be analyzed from several key perspectives:

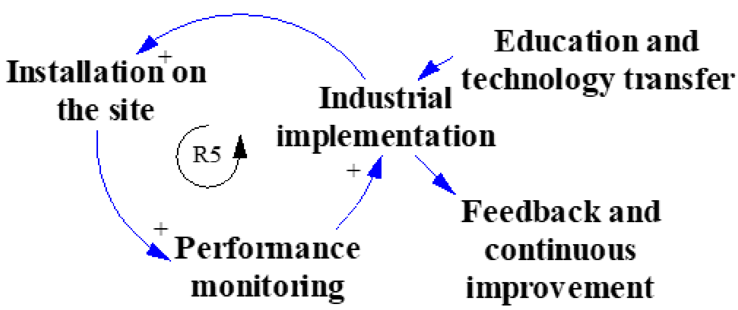
- **Enhancing Knowledge-Based and Engineering Capabilities:** Educational programs and university collaborations elevate the basic knowledge and technical-engineering skills of the workforce in the oil industry. This scientific and operational capability boost is essential for the absorption and development of new technologies in petro-refineries.
- **Facilitating Technology Localization:** Scientific and technological partnerships with universities and research centers enable the localized transfer of complex technologies such as the production of refinery catalysts. For instance, recent conferences on catalyst technology transfer in petrochemical and gas sectors have led to domestic production and development through joint efforts between Iranian universities, knowledge-based firms, and foreign companies.
- **Reducing Dependence on Imports and Sanctions:** Localizing technologies through training and academic collaboration reduces reliance on imported technologies and equipment, thus mitigating the impact of sanctions. This is particularly evident in the domestic production of catalysts that were previously imported.
- **Creating a Suitable Environment for Talent Attraction and Retention:** Educational programs and academic collaborations provide an environment that attracts committed young professionals to the industry, enabling them to apply their knowledge toward petroleum technology development. This contributes to sustainable technological advancement in petro-refineries.
- **Facilitating Industry–Academia Interaction:** System models show that technology transfer from academia to industry is among the most effective channels for technological development, and identifying success factors in this interaction can enhance the transfer process.

Industrial Implementation

The reinforcing role of industrial implementation in technology diffusion is depicted as reinforcing loop R5 in Figure 4.

Figure 4

Reinforcing Loop R5 in Technology Diffusion



Fundamentally, without industrial implementation, technology diffusion cannot truly exist. Among the critical aspects of implementing disseminated technology is performance monitoring, which plays a crucial and vital role in the technology transfer process in Iran’s petro-refinery sector and can be examined from several key angles:

- **Identifying Deviations and Operational Issues:** Continuous performance monitoring helps detect deviations from planned programs and execution problems of disseminated technologies, enabling timely corrective actions to optimize the technology transfer process.
- **Increasing Transparency and Accountability:** Regular monitoring and precise reporting allow stakeholders and investors in petro-refinery projects to assess actual performance, thereby increasing accountability in technology

implementation. This boosts trust in the technology transfer process and facilitates greater investment.

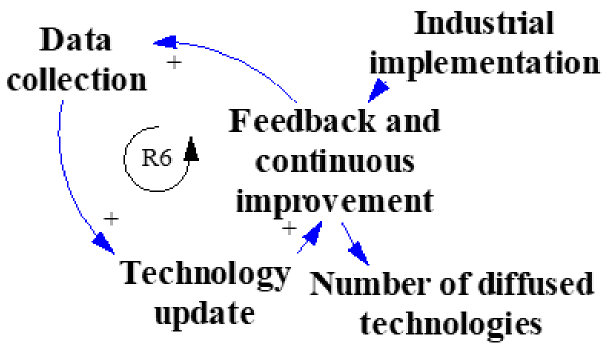
- **Improving Project Scheduling and Management:** Performance monitoring—especially if conducted on a daily or weekly basis—helps identify financial, technical, and managerial problems early, preventing project delays. This expedites the deployment of new technologies in petro-refineries.
- **Enhancing Efficiency and Profitability:** Accurate performance monitoring enables petro-refinery units to maintain optimal operational conditions, increase production of petrochemical and petroleum products, and consequently improve project profitability and the value chain across the oil and gas sector.
- **Supporting Industrial Development Policies:** Through continuous monitoring, the achievement of strategic goals in the development of the petro-refinery industry can be evaluated, allowing policymakers to adjust plans and provide appropriate support based on real-world data.

Feedback and Continuous Improvement

The feedback and continuous improvement of disseminated technologies play a transformative role in the technology transfer process within Iran's petro-refinery industry. The related reinforcing causal loop is illustrated in Figure 5.

Figure 5

Reinforcing Loop R6 in Technology Diffusion



The process of feedback and continuous improvement transforms technology transfer from a one-time event into a dynamic and sustainable process by creating learning loops, correcting weaknesses, and adapting technologies to local needs. Its key impacts include:

Enhancing Technology Adaptation to Local Conditions

- *Optimization Based on Operational Feedback:* Data derived from the actual performance of technology (such as energy consumption, product quality, or equipment durability) assist in design modifications or parameter adjustments tailored to Iran's specific conditions (e.g., domestic crude oil quality or refinery climate zones).
- *Reducing Dependence on External Solutions:* Continuous improvement of imported technologies enables the development of localized versions (e.g., catalysts compatible with Iran's gas composition).

Strengthening the Organizational Learning Cycle

- *Development of Domestic Technical Knowledge:* Feedback collected from production lines serves as a foundation for staff training and the institutionalization of knowledge within organizations.
- *Enhancing Industry–Academia Collaboration:* Issues identified through feedback are transformed into university research projects.

Reducing Costs and Increasing Competitiveness

- *Eliminating Inefficient Processes:* Continuous improvement based on feedback reduces waste, energy consumption, and production downtime.
- *Competing in Global Markets:* Technology updates (e.g., refining processes for low-sulfur fuel

production) make competition with international products possible.

Accelerating Innovation and Domestic Technology Development

- *Completing the Technology Value Chain:* Operational feedback reveals blind spots in imported technologies and opens pathways for domestic innovations (e.g., more efficient reactor designs).
- *Supporting the Circular Economy:* Environmental feedback enables continuous improvements in waste recovery or green technologies (e.g., CO_2 capture).

International Collaborations

The impact of international collaborations on technology transfer in Iran's petro-refineries is as follows:

- **Access to Advanced Technologies and Global Know-How:** Cooperation with companies and countries such as South Korea and other developed nations enables the transfer of state-of-the-art refining and petrochemical technologies. These collaborations help Iran apply complex, cutting-edge technologies in petro-refinery projects and benefit from international expertise.
- **Attracting Foreign Investment and Facilitating Project Financing:** International partnerships are often accompanied by joint investments, which not only provide financing but also bring in technical resources and modern equipment. This increases the construction and operational capacities of petro-refineries while reducing financial and technical risks.
- **Strengthening the Engineering and Technical Capabilities of Domestic Firms:** International cooperation facilitates the transfer of knowledge and technical skills to Iranian firms. This allows domestic companies to enhance their engineering and operational capabilities and play a more active role in future projects.
- **Creating Communication Networks and Global Market Access:** Participation in international conferences and exhibitions—such as the Iran Petrochemical Forum (IPF)—offers opportunities for dialogue, showcasing domestic technologies, and attracting new collaborations, all of which support export market development and boost competitiveness.
- **Facilitating Technology Localization and Reducing Import Dependency:** Technology transfer through international partnerships, followed by localization, enables Iran to internalize a significant portion of its technology needs. This reduces the effects of sanctions and enhances technical independence.

Therefore, the influence of international collaborations on the causal loop diagram of technology diffusion in Iran's petro-refineries can be considered positive.

International Sanctions

International sanctions exert significant and multifaceted effects on the diffusion and transfer of technology in Iran's petro-refinery industry. These effects can be categorized as follows:

Impact of Sanctions on Technology Diffusion and Transfer in the Petro-Refinery Industry:

- **Restricted Access to Advanced Technologies:** Sanctions limit Iran's access to modern technologies, equipment, and global know-how, posing a serious obstacle to upgrading and modernizing refinery technologies. Many refineries and petrochemical complexes operate with outdated equipment, and sanctions have slowed the adoption of new technologies.
- **Reduced Foreign Investment and Project Financing:** Sanctions have discouraged foreign companies and investors from participating in Iran's petro-refinery projects. This financial limitation poses challenges to implementing technology transfer initiatives and infrastructure development.
- **Increased Emphasis on Refinery Development and Technology Localization:** Given sanction-related constraints, Iran has pursued a strategy of expanding its refinery sector to reduce dependence on crude oil exports by producing high-value-added products. This strategy fosters technology localization and enhances self-sufficiency.
- **Impact on Exports and Global Markets:** Sanctions have limited crude oil exports, but petro-refinery products—due to their diversity and market reach—are less susceptible to sanctions and easier to sell. This has positioned refinery development as a strategic response to economic sanctions.
- **Slower Technology Development and Technological Backwardness:** Sanctions have

slowed the pace of technological progress in the petrochemical and refinery industries, causing Iran to lag behind global competitors in some areas.

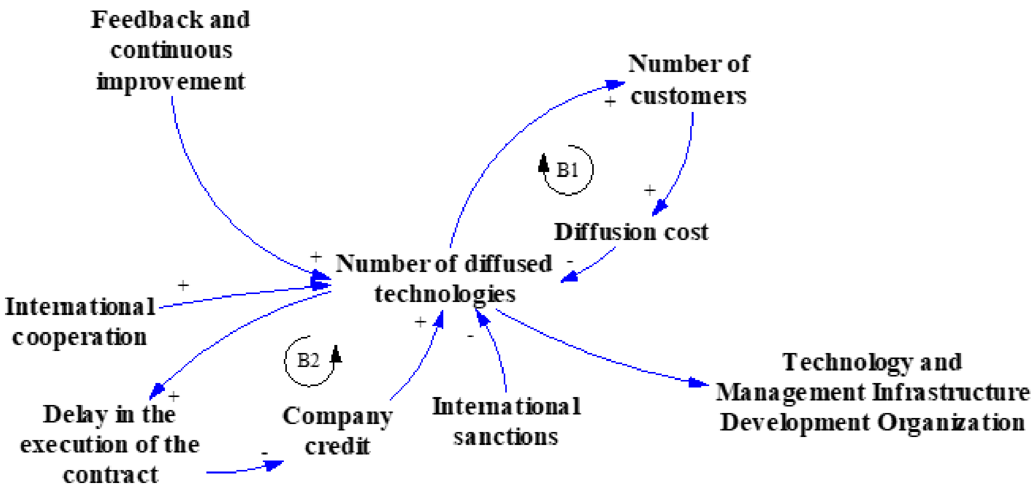
Overall, the impact of sanctions on the causal loop diagram of technology diffusion in Iran's petro-refineries should be considered negative. Industry experts also confirm this assessment.

Number of Technologies Disseminated

The number of disseminated technologies can significantly influence delays in contract execution and the credibility of companies involved in the technology transfer process within Iran's petro-refinery industry. This issue is governed by two balancing loops, B1 and B2, illustrated in Figure 6.

Figure 6

Diagram of Balancing Loops B1 and B2 in Technology Diffusion



The impact of the number of disseminated technologies on contract execution delays can be analyzed from the following perspectives:

- **Increased Complexity and the Need for Precise Management:** As the number of technologies deployed in projects rises, technical and managerial complexity increases. Without proper management, this can cause delays in contract execution, as each new technology requires coordination, training, and adaptation to local conditions.
- **Delays Due to Localization and Training Requirements:** New technologies typically require workforce training and localization. An increase in the number of technologies can prolong these processes, thereby extending project timelines.

Impact of Disseminated Technology Volume on Company Credibility:

- **Enhanced Credibility with Successful Implementation:** Companies that successfully implement a higher number of disseminated technologies strengthen their technical and operational reputation and improve their competitive position in the market.
- **Reduced Credibility Due to Delays and Failures:** Conversely, if the number of technologies is high but companies experience delays or technical failures, their credibility diminishes, and employer and partner trust declines.

Overall, given that an increase in the number of disseminated technologies in Iran's petro-refineries can lead to greater delays in contract execution and undermine company credibility, experts identify this as a balancing loop in the technology diffusion causal diagram, represented as B1 in Figure 6.

Furthermore, the number of technologies disseminated in the technology transfer process significantly affects the number of clients and the costs associated with diffusion, as explained in the following sections.

Impact of the Number of Technologies Disseminated on the Number of Clients

- **Increased Attractiveness and Variety of Technologies for Clients:** As the number of disseminated technologies increases, the range of technology options and applications expands, attracting more clients from different sectors of the petro-refinery industry. Clients, based on their specific needs, can select suitable technologies from among the available options, which contributes to the expansion of the technology market.
- **Strengthening Trust and Credibility in Domestic Technologies:** The successful dissemination of a larger number of technologies increases client confidence—both domestic and international—in the technical capabilities of Iranian companies and research centers, thus increasing the client base.
- **Facilitating Petro-Refinery Development and Investor Attraction:** A broader portfolio of technologies enables more petro-refinery projects to benefit, which contributes to industry development and attracts both domestic and foreign investment.

Impact of the Number of Technologies Disseminated on Technology Diffusion Costs

- **Reduced Diffusion Costs Due to Economies of Scale:** Increasing the number of disseminated technologies and their broader adoption leads to a reduction in the unit costs of development, training, localization, and diffusion. In other words, with market and client expansion, costs are distributed more efficiently, making technology diffusion more cost-effective.
- **Increased Initial Costs in the Case of Complex Technologies:** On the other hand, if the number of technologies is high and the technologies themselves are complex, costs associated with training, knowledge transfer, and local adaptation may increase. Thus, efficient technology diffusion management is essential to control these expenses.
- **Need for Investment in Supportive Infrastructures:** With a rise in the number of disseminated technologies, the demand for the development of educational, research, and technical support infrastructures also grows, which impacts the overall cost of technology diffusion.

In general, the increase in the number of technologies disseminated in Iran's petro-refineries is recognized by experts as a balancing loop in the technology diffusion system, and is represented as B2 in Figure 6.

Model Validation

Model testing and validation enhance the model's reliability and reinforce confidence in its practical applicability. Structural validation of the model takes precedence over behavioral validation, meaning that the model's behavior can only be assessed after confirming its structural validity (Motamedi, Majid; Darvish Motavalli, Mohammad Hossein, 2025).

Given that the model in this study is qualitative, qualitative model validation methods were implemented based on expert opinion as follows:

1. **Structural Consistency Test**: The purpose of this test was to examine the consistency of causal relationships and feedback loops. Experts were asked to explain how a change in one variable affects others. For example, they were asked: "If variable X increases, why does variable Y decrease? Is this relationship valid under all conditions?"
2. **Qualitative Extreme Conditions Test:** This test aimed to evaluate the model's behavior in unconventional scenarios. Experts were asked, for instance: "If variable X reaches zero, how would the system behave?"
3. **System Boundary Analysis:** The objective of this test was to ensure the comprehensiveness of variables included in the model. For example, experts were provided with a list of model variables and asked to identify any omitted factors.

Ultimately, the model validation results indicated that the proposed model satisfactorily met all the criteria of the aforementioned tests. Therefore, it is deemed a suitable model for evaluating the system dynamics of technology diffusion in Iran's petro-refinery sector.

4. Discussion and Conclusion

The findings of this study offer a comprehensive understanding of the mechanisms underlying technology diffusion in Iran's petro-refining industry using a system dynamics modeling approach. The model developed in this research identified nine key causal loops—both reinforcing and balancing—that influence the diffusion process. These loops include: the role of technology development organizations, needs identification and feasibility analysis, negotiation and contracting skills, training and technology transfer, industrial implementation, feedback and continuous improvement, international collaboration, international sanctions, and the number of technologies disseminated. The interactions among these variables demonstrate that technology diffusion is not a linear process but rather a complex and adaptive system influenced by both internal capabilities and external constraints.

One of the key results was the centrality of technology development organizations and managerial infrastructures in initiating and sustaining the diffusion of technology (loop R1). These entities serve as anchors for structuring knowledge transfer, coordinating stakeholders, and establishing standards for industrial implementation. This finding is aligned with (Esmaeili et al., 2025), who emphasized that a system-level approach to organizational support significantly enhances the absorption and localization of advanced technologies. It also confirms earlier work by (Khamseh, 2023) that highlights the necessity of organizational readiness and capacity-building in managing the complexity of technology transfer. Furthermore, the integration of technology development organizations into strategic planning ensures feedback-driven decision-making, thereby strengthening Iran's resilience to external shocks and enabling long-term sustainability.

The role of needs identification and feasibility analysis (loop R2) was found to be foundational in determining the appropriateness and cost-effectiveness of technology adoption. Technologies that are misaligned with domestic feedstock characteristics, market demand, or geographic constraints risk underperformance and wastage. This finding reinforces the view of (Ren et al., 2023), who suggested that technology transfer in high-tech firms must be resource-sensitive and contextually grounded to support a circular economy. Similarly, (Radfar & Khamseh, 2021) emphasized that pre-transfer feasibility studies reduce the risks of investment misdirection and accelerate the effective operationalization of imported technologies.

Another crucial element identified in the model was negotiation and contracting skills (loop R1). These were shown to be critical for overcoming sanctions-related barriers, protecting intellectual property rights, and ensuring legal alignment with both domestic and international frameworks. The findings echo (Hayter et al., 2023), who identified the strategic function of contract governance in the success of academic entrepreneurship and technology commercialization. The reinforcing role of negotiation also confirms (Sadeghi et al., 2022), who argued that Iran's polymer pipe and fittings industry achieved higher levels of technology localization when contract design accounted for performance-based clauses, dispute resolution, and adaptive risk-sharing mechanisms.

Training and knowledge transfer mechanisms (loops R3 and R4) were highlighted as core enablers for capacity-building and the institutionalization of technological know-how. The study found that partnerships with universities, research centers, and knowledge-based firms significantly accelerated the localization of advanced technologies such as catalyst production. This finding corresponds with (Barros et al., 2020), who concluded that the interaction between knowledge management and technology transfer leads to the development of firm-specific capabilities. Additionally, the feedback-based learning emphasized by (Hamilton & Philbin, 2020) supports this result, suggesting that organizational learning loops derived from field experience promote innovation diffusion across complex industrial systems.

The reinforcing loop related to industrial implementation and performance monitoring (R5) emerged as a pivotal stage in ensuring that transferred technologies transition from prototype to full-scale operationalization. This aligns with (Mykytyuk & Kasych, 2020), who posited that feedback loops in infrastructure-intensive industries must be tightly integrated with project timelines and operational audits to ensure efficiency and adaptability. In particular, the study revealed that without consistent performance monitoring, localized technologies may regress due to mismatches in expected versus actual functionality, delays in maintenance, and operational underperformance.

The study also validated the importance of feedback and continuous improvement (loop R6), which transforms the diffusion process from a static transaction into an iterative and evolutionary learning system. The operational data collected during implementation informed real-time decision-making, helped identify bottlenecks, and contributed to the customization of solutions for local contexts. This finding supports the SPACE-RL innovation transfer model proposed by (Bilan et al., 2023) and (Artyukhov et al., 2023), who emphasized the importance of "learning resilience" in linking science and business for sustainable diffusion of innovation.

International collaboration (loop R7) was shown to be a positive reinforcing factor that provided access to advanced knowledge, investment resources, and joint research opportunities. However, this effect was strongly moderated by international sanctions (loop R8), which emerged as a balancing loop that restricted access to critical technologies, limited financial flows, and reduced institutional willingness to engage with Iranian partners. These findings are consistent with the policy constraints discussed by (Jalilzadeh Tabrizi & Jalalpour, 2023), who argued that global sustainable development policies must incorporate equitable access mechanisms for emerging economies facing geopolitical constraints.

The number of technologies disseminated (loop B2) was also found to have a dual effect. While a larger portfolio increased the attractiveness of domestic technologies for clients and expanded investment potential, it also introduced complexity that could delay contract execution and reduce implementation quality if not managed properly. This supports (Motamedi & Darvish Motavalli, 2025), who demonstrated that balancing feedback loops are essential in maintaining stability within dynamic systems. It also reflects findings by (Zhenxu et al., 2024), who modeled the threshold effects in policy implementation, showing that beyond a certain level of complexity, performance and efficiency may deteriorate without system-wide harmonization.

In summary, the results underscore the importance of using a system dynamics approach in evaluating the multi-level interactions involved in technology diffusion. Each reinforcing and balancing loop contributes to the system's overall behavior and highlights the need for a coordinated, adaptive, and feedback-driven strategy to manage technology diffusion in a high-stakes industry like petro-refining.

Despite the robustness of the model and its alignment with empirical observations, this study has several limitations. First, the model is based on qualitative data derived from expert judgment, which, although validated, may still be influenced by subjective biases. Second, while the system dynamics approach offers rich insights into causal interdependencies, it may not fully capture sudden external shocks, such as abrupt regulatory changes or geopolitical escalations, that can significantly alter technology diffusion trajectories. Third, the study focused solely on Iran's petro-refining industry, limiting the generalizability of the model to other industrial contexts without further calibration.

Future research could extend this model by incorporating quantitative variables and conducting sensitivity analysis to evaluate the robustness of causal loops under different policy scenarios. Comparative studies across other resource-based industries or national innovation systems could also be conducted to determine the universality or context-specificity of the identified loops. Moreover, future work could explore how digital technologies, such as blockchain and AI, can enhance transparency, monitoring, and feedback in technology transfer systems. Longitudinal studies tracking real-time data across technology transfer projects would also add empirical weight to the model's predictive validity.

To enhance technology diffusion in Iran's petro-refining sector, policymakers should strengthen the institutional capacity of technology development organizations and embed continuous monitoring mechanisms across all stages of the transfer process. Strategic partnerships with universities and international collaborators must be formalized and protected through robust legal frameworks. Training programs should be tailored to the specific technological competencies required for each diffusion cycle. Moreover, government and industry leaders must harmonize regulatory, financial, and operational frameworks to ensure that the adoption of advanced technologies translates into measurable economic and environmental outcomes.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

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