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An Analysis of Supply Chain Macro-Strategies in the Context of Industry 4.0 with a System Dynamics Approach (The Case of: Iran's Steel Supply Chain)

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ABSTRACT

Forward-thinking decisions and adopting cutting-edge technologies typically influence the management of large, multi-level supply chains. Given the various raw materials, semi-finished products, and final goods in these multi-level supply chains, balancing imports and exports is one of the most significant challenges and macro-level issues facing countries. System dynamics simulation is a powerful tool for analyzing macro-level issues, as it can predict future system behavior based on current conditions. In this research, Iran's steel supply chain was selected as a case study to assess future trends at the macro level under the influence of Industry 4.0. Industry 4.0 encompasses a range of innovative technologies that can improve supply chain efficiency. For this purpose, AnyLogic software was used to simulate the model. According to the system dynamics simulation results, keeping a balance between supply and demand at each stage of the supply chain plays a crucial role in increasing efficiency and profitability. Additionally, macro-level policies such as budget allocation, export rate, and support for investments in various parts of the supply chain directly impact this chain's performance. Sensitivity analysis revealed that increasing the budget and production capacity in the direct reduced iron (DRI) and crude steel sectors has a greater impact on the overall profitability of the chain, and exporting crude steel can be a significant way to increase revenue and foreign exchange earnings for the country.

Keywords

System dynamics simulation, Multi-level supply chain, Supply chain macro-level, Industry 4.0, Iran's steel supply chain.

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1. Introduction

Industry 4.0 has transformed manufacturing by introducing digital technologies to create smart, interconnected factories. This connectivity enables real-time data collection and analysis, enhancing efficiency, productivity, and flexibility.

This concept can also be manifested in large supply chains by integrating the capabilities of manufacturing units into cloud platforms (Zhu et al., 2022).

Large supply chains, with their multiple levels of producers and consumers and diverse interconnections, present significant complexities in management and control. Global competition in recent years has compelled organizations to produce products with lower costs, higher quality, and greater reliability and flexibility. In this regard, supply chains have significantly improved production efficiency (Luthra and Mangla, 2018). Large supply chains are important for gaining a competitive advantage in the global market. Since researchers have placed greater emphasis on supply chain research, a broad literature has been established in this field (Kache and Seuring, 2017).

Multi-level supply chains, which cover raw materials, semi-finished products, and finished products from production stages to end consumption, can extend from the local or national level to the global level. Imports and exports are among the most important factors influencing large, multi-level supply chains, and various factors can contribute to improving efficiency and increasing the value of the supply chain (Tahami and Fakhravar, 2020; Golgeci et al., 2020). These include:

(1) **Using domestic resources or imports:** If the raw materials for each level of the supply chain are produced domestically, choosing between using these raw materials or importing raw materials from abroad can be a significant challenge.

(2) **Meeting domestic needs or exports:** Exporting products to other countries can contribute to trade diversification and provide greater resilience in the face of various regional risks (such as economic or natural crises). If products are produced in sufficient quantities domestically and there is no need to export, it can help meet domestic needs and strengthen the domestic economy.

Overall, macro-level supply chain strategies and the balance between exports and imports in multi-level supply chains contribute to improved performance and increased added value, leading to better efficiency. Macro-level supply chain strategies are pivotal in shaping a country's economy. These strategies encompass a wide range of coordinated and integrated approaches to manage the entire supply chain, from procuring raw materials to delivering finished goods to consumers and determining the level of imports and exports. By improving the flow of goods and services, countries can gain a competitive advantage in the global market (Gereffi et al., 2021).

The steel supply chain is a complex multi-level supply chain that begins with iron ore extraction and ends with producing steel products. Each stage depends on the next in this chain, and any disruption in one stage can affect the entire chain (Figure 1). In this context, presenting a model that considers the macro-level supply and demand variables of products throughout the steel supply chain (from iron ore, concentrate, pellet, direct reduced iron, crude steel, and steel consumption and recycling) and using simulation techniques, models the future changes of this industry, can play a significant role in decision-making in the steel supply chain to improve specific production methods.

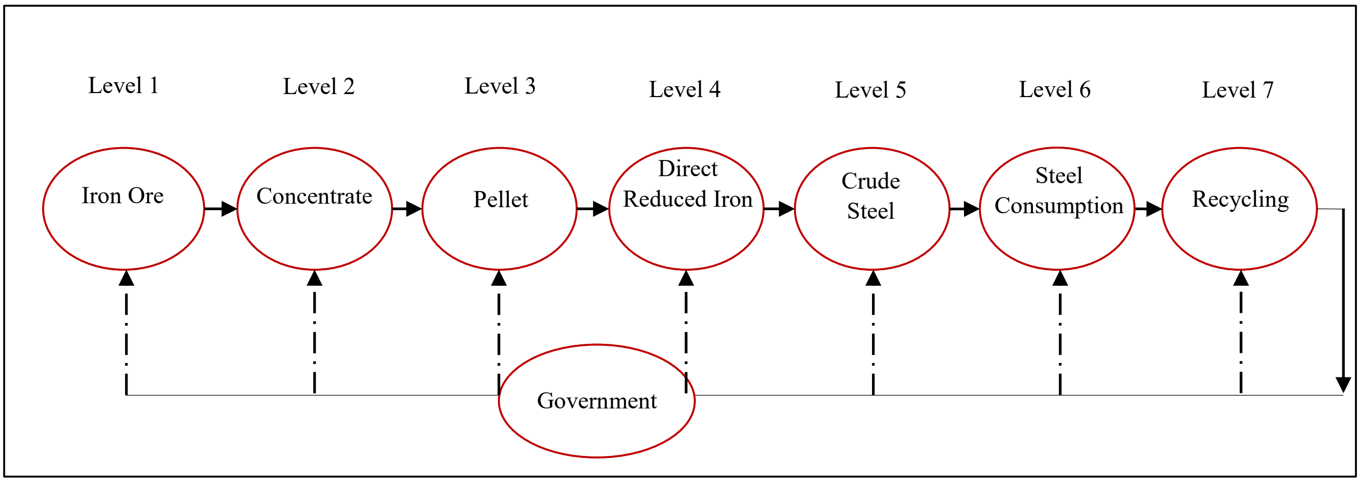

Figure 1. Steel supply chain

Iran's steel supply chain has numerous comparative advantages in terms of energy availability, energy costs, raw material and iron ore mines, and a skilled workforce at a low cost. These advantages, coupled with adopting advanced production technologies and the right strategies, can play a significant role in competing in the global steel market. Table 1 shows the crude steel production of the world's top 20 producers over the decade ending in 2022. Iran currently ranks 10th (Steel Statistical Yearbook, 2022).

Table 1. The world's top 20 producers over the decade ending in 2022

Rank (2022)	Year / Country	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
—	World	1649	1670	1620	1606	1675	1808	1874	1878	1952	1885
1	China	779	823	804	787	832	920	995	1065	1033	1018
2	India	81	87	90	96	102	109	111	100	144	154
3	Japan	111	111	105	105	105	104	99	83	96	89
4	United States	87	88	79	79	82	87	88	73	86	81
5	Russia	69	72	71	71	71	72	72	72	76	72
6	South Korea	66	72	70	69	71	73	71	67	70	66
7	Turkey	35	34	32	33	38	37	34	36	40	35
8	Germany	43	43	43	42	44	42	40	36	40	37
9	Brazil	34	34	33	30	34	35	33	31	36	34
10	Iran	15	16	16	18	22	25	26	29	29	31
11	Italy	24	24	22	23	24	25	23	20	24	22
12	Taiwan	22	23	21	22	23	23	22	21	23	21
13	Vietnam	6	6	6	8	10	16	18	20	23	20
14	Ukraine	33	27	23	24	23	21	21	21	21	6
15	Mexico	18	19	18	19	20	20	18	17	19	18
16	Indonesia	3	4	5	5	5	6	8	9	14	16
17	Spain	14	14	15	14	15	14	14	11	14	12
18	France	16	16	15	15	16	15	14	12	14	12
19	Canada	12	13	13	13	14	13	13	11	13	12
20	Egypt	7	7	6	5	7	8	7	8	10	10

Figure 2 depicts the trend in crude steel production for the top ten crude steel-producing countries from 2013 to 2022. Given that China accounts for 54% of the world's crude steel production, it has been excluded from the chart to better visualize other countries' production trends. As observed, Iran's crude steel production has shown an upward trend over the past decade.

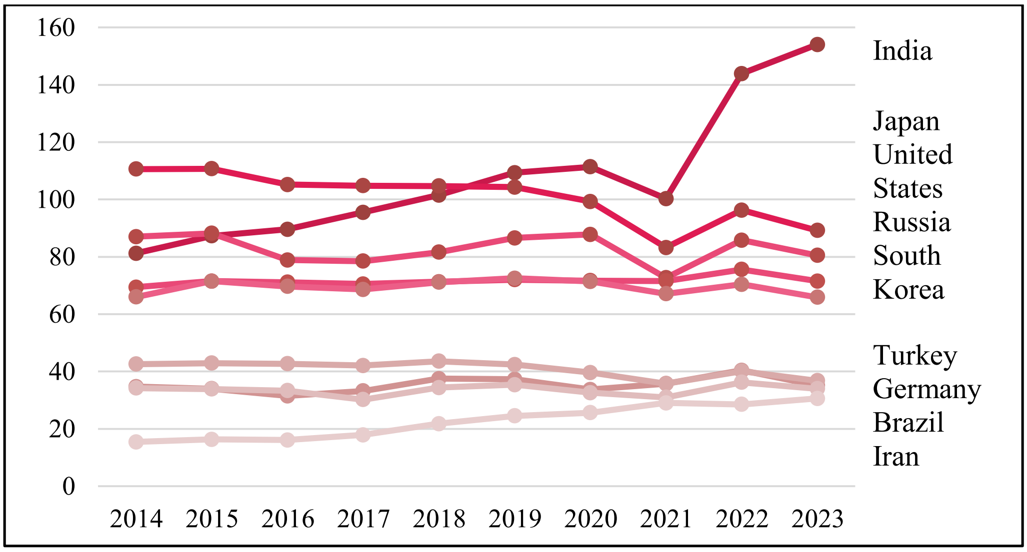

Figure 2. The trend in crude steel production for the top ten countries from 2013 to 2022 (Except China)

Figure 3 illustrates the top ten crude steel producers in 2022. China ranks first with a 54% share of the world's crude steel production, while Iran is the tenth largest producer with a 0.16% share.

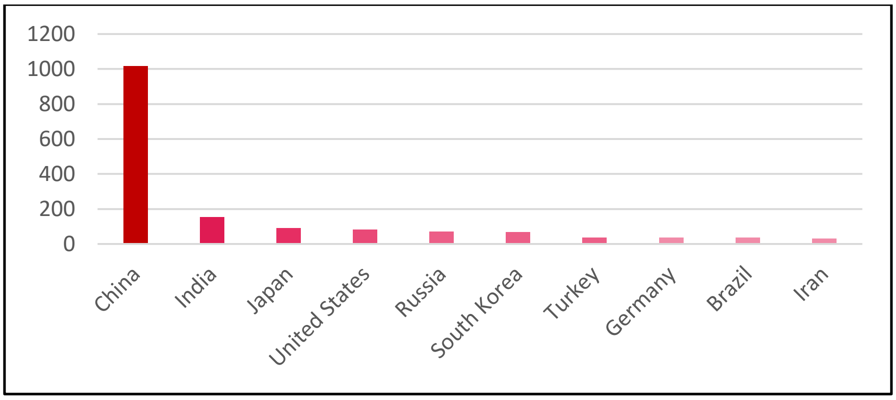

Figure 3. The top ten crude steel producers in 2022

Therefore, based on these statistics, Iran's steel supply chain can be a suitable case study for validating our model. This research uses system dynamics simulation to model the multi-level supply chain. Forrester first developed system dynamics to understand the structure and dynamics of a system. It is a method for studying, analyzing, and simulating dynamic social, economic, and managerial systems, ultimately leading to recommendations for improving them.

This research aims is to develop a comprehensive strategy for macro-level policies in a multi-level supply chain. The main variables include export rates, import rates, production rates, capacity development costs, capacity creation rates, capacity depreciation rates, product inventory, excess demand, demand for products at each level, demand growth rate, product sales rate, and total profit for each level of the multi-level supply chain This research will be conducted over a ten years.

The research question is: How can system dynamics modeling be used to develop a comprehensive strategy for macro-level policies in Iran's steel supply chain? And will these policies be affected by Industry 4.0?

In the following sections of this research, the literature review is presented in Section 2. The research methodology is discussed in Section 3, and the modeling results are presented in Section 4. Finally, the results are summarized in Section 5.

2. literature review

In order to conduct this research and identify the key variables and parameters of the problem, this study first reviewed the previous literature in this field. Generally, these research works can be categorized into three main groups (Figure 4).

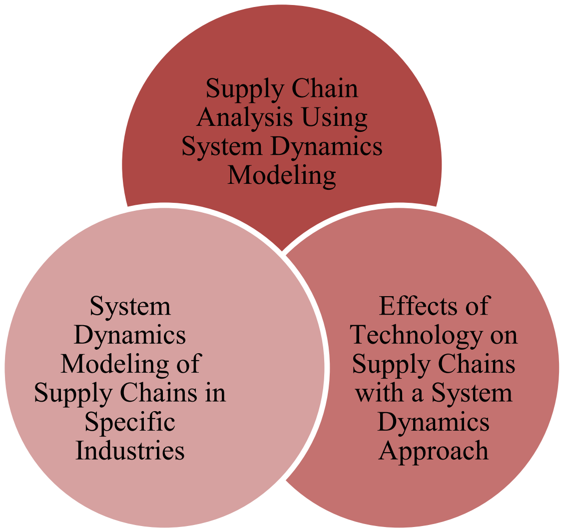

Figure 4. General classification of previous studies

2.1. Supply chain analysis using system dynamics modeling

This group of articles uses system dynamics to analyze and model supply chains. These articles delve into the concept of supply chain, production rate, inventory level, and other influencing factors. Özbayrak et al. (2007) modeled a supply chain system using system dynamics to analyze and understand the dynamic behavior of supply chains. The authors limited the system dynamics chain to a factory and production system, considering variables such as production rate, inventory level, order rate, lead time for raw materials, and production time in this model.

Ghadge et al. (2020) developed a model using system dynamics in a study aimed at analyzing the impact of implementing Industry 4.0 on supply chains and creating an implementation framework considering potential drivers and barriers. Four sets of variables influencing Industry 4.0 were used in this dynamic model. These four sets included strategic, technological, legal, ethical, and organizational factors. This study discussed several implementation challenges and proposed a framework for effectively adapting and transferring the Industry 4.0 concept to the supply chain. Rebs et al. (2019) also studied system dynamics modeling for sustainable supply chain management by reviewing the literature and a system thinking approach. They tracked global economic systems and environmental and social impacts in previous studies. Although system dynamics modeling is suitable for simulating and analyzing complex and dynamic systems and supporting long-term and strategic decision-making, this article presents economic, environmental, and social criteria related to macro and micro levels of supply chain dynamics analysis.

2.2. Effects of technology on supply chains with a system dynamics approach

In this group, system dynamics is used to investigate the impacts of technologies such as Industry 4.0 and blockchain on supply chains and to propose implementation frameworks. For instance, Nuñez Rodriguez et al. (2021) developed a system dynamics model for additive manufacturing supply chain management, aiming to visualize supply chain behavior when adopting a disruptive technology like additive manufacturing. This model was organized through causal loop and stock-flow diagrams with thirteen supply chain-related variables, covering the supplier, manufacturer, and core manufacturer distributor. Variables such as production time and product inventory levels were considered. Additionally, Gao and Ma (2020) constructed and analyzed the supply chain of manufacturing companies undergoing the service transformation using system dynamics simulation. Subsequently, they investigated the bullwhip effect's characteristics in the supply chain's service transformation. Finally, suitable policies for the supply chain were suggested. Using system dynamics modeling, Mangla et al. (2021), mapped the milk supply chain to uncover information flow among different members for higher traceability. Then, they examined the social impacts of blockchain technology in the milk supply chain to establish the necessary social sustainability.

2.3. System dynamics modeling of supply chains in specific industries

This group uses system dynamics to model and improve supply chains, focusing on specific industries. Mohammadi et al. (2022) developed a dynamic simulation model for the steel supply chain, considering complexities and interactions. This study considered four steel supply chain levels: concentrate, pellet, sponge iron, and steel. The grade and tonnage of iron ore, iron ore supply constraints, production costs, and final profit were the variables examined in this model. Alamerew and Brissaud (2020) that presents a model to represent a complex reverse logistics system for product recovery using a system dynamics approach. They considered costs, revenue, and strategic and regulatory decisions for dynamic modeling.

Additionally, the main enablers and challenges for recovery were presented. Finally, suitable strategies for improving this logistics system were provided. Olivares-Aguila and ElMaraghy (2021) introduced a system dynamics framework to observe supply chain behavior and evaluate the effects of disruptions. The effects of disruptions on service levels, costs, profits, and supply chain inventory levels were analyzed. The framework and findings were used to define policies and support decision-making related to supply chain design. Elyasi and Teimoury (2023) considered the Iranian rice supply chain a system and modeled economic sustainability using system dynamics. They used the soft systems methodology, critical systems heuristic, and interactive planning methodology to define social and environmental sustainability. Finally, they presented seven implementable policies for supply chain managers to achieve sustainability in this supply chain.

Table 2 outlines the objectives, methods, main findings, and gaps of each study to clearly highlight the position and contribution of the present research in addressing existing gaps.

Table 2. Summary of previous studies and identified gaps

Study	Objective	Methods	Key Findings	Identified Gaps
Özbayrak et al. (2007)	Model dynamic behavior of supply chains	System dynamics modeling	Highlighted internal factory-level dynamics	Limited to single-factory analysis without multi-level supply chain context
Ghadge et al. (2020)	Analyze Industry 4.0's impact on supply chains	System dynamics with barriers analysis	Developed a framework for Industry 4.0 implementation	Lacks empirical testing in specific industries like steel
Rebs et al. (2019)	Sustainable supply chain management	System thinking approach with sustainability criteria	Established macro and micro sustainability analysis	Limited focus on long-term economic impacts of Industry 4.0
Nuñez Rodriguez et al. (2021)	Assess additive manufacturing in supply chains	Causal loop diagrams and stock-flow	Demonstrated supply chain behavior with disruptive technologies	Specific to additive manufacturing without insights into traditional industries
Gao and Ma (2020)	Service transformation in manufacturing supply chains	System dynamics with bullwhip effect analysis	Explored effects on service-oriented transformations	No exploration of technology
Alamerew and Brissaud (2020)	Reverse logistics for product recovery	System dynamics modeling for sustainability	Developed policies for logistics recovery systems	Does not address supply chains
Mohammadi et al. (2022)	Steel supply chain dynamics for Iran	System dynamics	Investigated multi-level steel supply chain in Iran	Limited to economic factors; lacks broader Industry 4.0 technology implications
Olivares-Aguila and ElMaraghy (2021)	System dynamics for supply chain design	Defined policies for resilience against disruptions	Disruptions in supply chain systems	Limited to single-factory analysis without multi-level supply chain context

The reviewed literature demonstrates the valuable role of system dynamics in modeling diverse supply chain factors, particularly in the context of Industry 4.0. These studies effectively simulate complex variables related to production rates, sustainability, and resilience within specific industries. However, many tend to concentrate primarily on economic factors, limiting their generalizability and applicability across different contexts. Moreover, there is a pressing need for longitudinal assessments that explore the long-term effects of emerging technologies, such as those associated with Industry 4.0, on supply chains.

Despite advancements in this area, examining macro-level supply chain policies using a system dynamics approach remains a relatively underexplored topic. Our research aims to innovate by analyzing key variables, including export and import rates, production rates, capacity development costs, capacity creation rates, depreciation rates, product accumulation, product demand, and profit margins across a multi-level supply chain. This comprehensive examination will enhance the understanding of the Iranian steel supply chain dynamics and shed light on the broader implications of Industry 4.0 adoption in similar contexts.

3. Method

Developing a suitable framework that allows for the evaluation and analysis of decisions, policies, and various scenarios of a multi-level supply chain requires considering a wide range of variables and relationships affecting the various factors of this supply chain. Therefore, choosing a suitable approach to model this issue is very important. In order to select a suitable approach, two main criteria were considered:

(1) First, our approach should be holistic and consider the dynamics of the supply chain as a coherent whole.

(2) Second, due to the large number of variables affecting this issue, the chosen approach should be suitable for comprehensive policy analysis.

Therefore, given that system dynamics is a powerful approach for analyzing complex and dynamic systems, this approach was used to model the problem.

System dynamics theory: System dynamics was first introduced by Forrester to identify the dynamics and structure of complex systems. This approach analyzes and examines complex dynamic social, economic, and managerial systems through simulation and provides suggestions for improvement. System dynamics helps us to examine issues from a systemic and overall perspective rather than identifying and defining each issue in detail.

System dynamics modeling is a process that includes various stages, such as defining and identifying the problem, defining the problem variables, defining the model boundaries, defining the model structure, defining mathematical relationships, running and validating the model, and designing and conducting Policies. All modeling issues begin with a real-world problem and end with designing and implementing policies to solve this problem. The stages of this method are shown in Figure 5 (Sterman, 2000; Mashayekhi and Ghili, 2010).

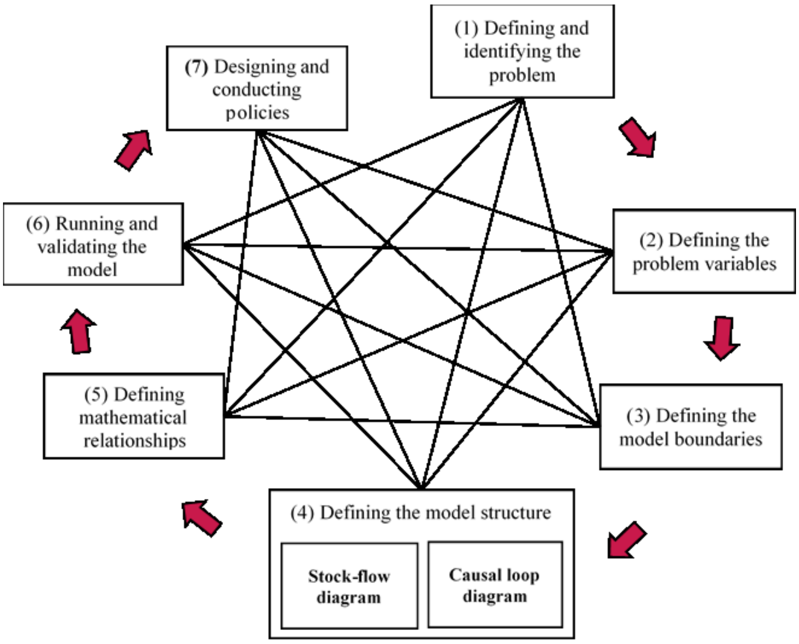

Figure 5. The stages of modeling by the systems dynamics method (Sterman, 2000 and Mashayekhi and Ghili, 2010).

In order to collect data for this research, 21 experts were involved, selected from managers and specialists of industrial complexes, including National Iranian Steel Company, Mobarakeh Steel Company, Alloy Steel Company, Chadormalu Mine, Arfa Steel Company, Golgohar Mine, Jahan Steel Company, Jalal'abad Iron Ore Mine, Zarand Steel Company, and Sanie Kavah Steel. This study used judgmental and snowball sampling methods to select experts. These methods, focused on gathering in-depth information from specialists, helped identify 21 experts for the research process. Field visits to steel production plants and interviews with managers and specialists further enabled the collection of expert insights and practical knowledge. Additionally, data has been obtained from relevant official sources, including the Iran National Steel Company and the Iran Statistics Center to complete the information.

4. Results

In this section, the author proceeds according to the steps outlined in Figure 5 and implements the seven main steps.

4.1. Defining and identifying the problem

Defining and identifying the problem is divided into two parts. The first part involves identifying the main problem regarding the macro policies of multi-level supply chains. The second part concerns identifying the case study that will be used to validate the model.

4.2. Identifying the problem

To identify the factors affecting the macro policies of multi-level supply chains and the variables influencing the formation of causal loop diagrams and stock-flow diagrams and to provide solutions and policies for improving current trends, a proper definition of the problem must first be provided. To this end, semi-structured interviews were conducted with research experts to discover and more accurately identify the system. The purpose and approach of systems dynamics modeling were briefly explained at the beginning of each interview. Then, discussions were held regarding the factors affecting the macro policies of the supply chain, the behavior of key variables over time, and the identification of the causes of these behaviors, variables influencing the formation of causal loops, and dynamic hypotheses, which include identifying how the interacting variables create behavior. Finally, solutions and policies for improving macro supply chain policies were presented.

4.2.1. Reference diagrams

In order to validate the model and conduct experiments, a case study must be selected. In order to examine the suitability of this case study for the developed model, reference diagrams must be drawn. Reference diagrams show the behavioral pattern of the model and lead to a better understanding of the important variables in the modeling process. The reference diagrams of our research include Figure 6 to 8.

Iran's steel production has increased from 30,000 tons in 1971 to over 30 million tons in 2023. The trend of steel production in Iran has almost always been upward in the years after the 1979 revolution. This growth trend is logical since the steel industry has always been one of Iran's major development goals. Considering that Iran's nominal steel production capacity is much higher than its actual production (about 60 million tons), it is predicted that the upward trend of Iran's steel production growth will continue in the coming years. Figure 6 shows the growth of Iran's steel production in recent years.

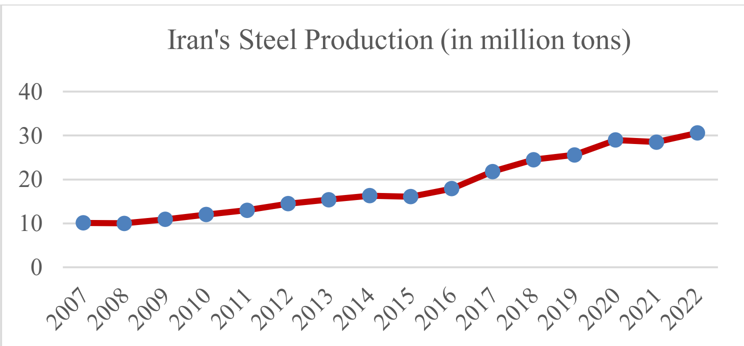

Figure 6. Steel Iran's Crude Steel Production from 2007 to 2022

The amount of iron ore extracted from Iran's mines has consistently shown an upward trend in recent years. Given the establishment of industrial units and steel production, the increase in iron ore extraction is natural. Figure 7 shows the growth trend of iron ore extraction in Iran in recent years.

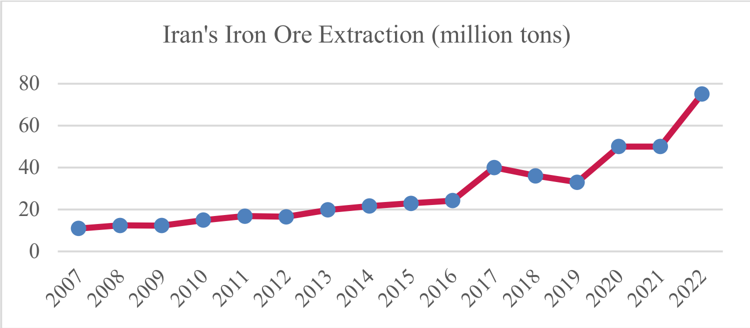

Figure 7. The amount of iron ore extracted between 2007 and 2022

As seen in Figure 8, Iran's steel exports have increased continuously from 2007 to 2022. This increase is due to factors such as the growth of Iran's steel production, the increase in global steel prices, and the improvement of transportation infrastructure. In 2022, Iran ranked ninth globally with 24.7 million tons of steel exports. Most of Iran's steel exports go to countries such as China, India, Turkey, Iraq, and Afghanistan.

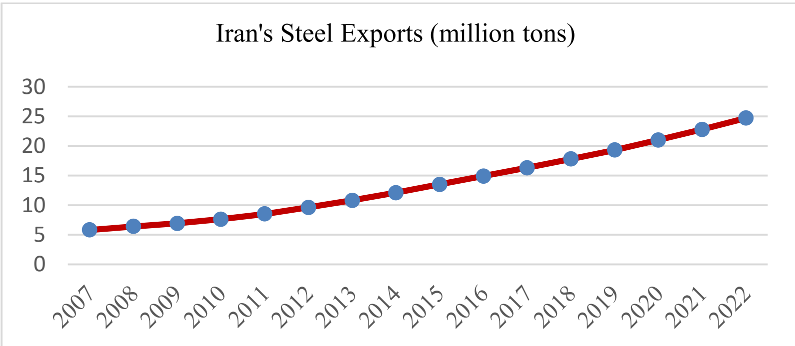

Figure 8. Iran's Steel Exports from 2007 to 2022

Based on Figure 8, the overall trend of the steel supply chain has shown an upward trajectory in most official statistical indicators over the past years. However, in some years, fluctuations in these diagrams can be observed due to the adoption and implementation of certain policies or the occurrence of specific events. By examining the temporal changes in Iran's steel production, iron ore production, and steel exports over the past decade, and considering that Iran's nominal steel production capacity significantly exceeds its actual production, and there are restrictions on the import and export of raw materials, intermediate products, and final products at all levels of this supply chain, a systems dynamics approach can be used to evaluate macro-level import and export policies.

4.3. Defining the problem variables

The next step in systems dynamics modeling is identifying the influential variables of the model. For this purpose, the content validity index was used to validate the model variables. This stage is one of the most important steps in systems dynamics modeling because the fundamental basis of causal loop diagrams and stock-flow models is the influential variables of the model. These variables are identified based on the research objectives, questions, and dynamic assumptions within the model's boundaries.

In this research, after a systematic review of the literature and conducting in-depth semi-structured interviews, an initial list of research variables and their relationships was identified, and based on this, a causal loop diagram and a stock-flow diagram were designed. Then, to ensure the validity of the identified variables, they were tested using a questionnaire based on the content validity index (CVI) assessment. This index determines the necessity of using each variable in the modeling process. The content validity index was first used Waltz and Bausell (1981). In using this index, research experts specify the relevance of each variable based on a four-part scale. Experts rate the relevance of each index according to their personal opinion, from 1 (Not Relevant), 2 (Item Needs Some Revision), 3 (Relevant but Needs Minor Revision), to 4 (Very Relevant). Finally, the content validity index for each variable is calculated as follows:

$$\text{CVI} = \frac{Number\ of\ experts\ rating\ the\ variable\ as\ 3\ or\ 4}{Total\ number} \quad (1)$$

The minimum acceptable value for the CVI is 0.79, and if the CVI for a variable is less than 0.79, that variable should be eliminated. The results of the test are presented in Table 3.

Table 3. Results of CVI Test

Number	Variable Name	Number of experts who rated the variable as 3 or 4	CVI
1	Development Costs	21	1
2	Production Capacity	21	1
3	Capacity Production Rate	21	1
4	Depreciation Rate	19	0.9
5	Product Accumulation	18	0.86
6	Export Rate	21	1
7	Import Rate	20	1
8	Over Demand	19	0.9
9	Production Rate	21	1
10	Demand	21	1
11	Demand Increase	21	1
12	Selling Rate	21	1
13	Profit	21	1
14	Total Profit	21	1

4.4. Defining the model boundaries

Every research should have a specific scope regarding time, place, and subject. Defining these boundaries ensures that the research results are reliable in application. The subject scope of this research is the structure of a multi-level supply chain, and the spatial scope is the steel supply chain in Iran.

In order to collect the data used in this research, sources, and data related to the Iranian steel supply chain from 2007 to 2022 have been used. The reason for this choice is that many important historical events of this supply chain have occurred during this period, and their effects have been observable, resulting in the possibility of analyzing the model's behavior. Additionally, a 15-year time frame is long enough to observe the effects of decision results. The temporal scope of the research covers the next ten years.

4.5. Defining the model structure

In this research, after identifying the important variables and parameters affecting the macro-level policies of the multi-level supply chain, drawing reference diagrams, and identifying important trends and patterns of the supply chain, the dynamic model of the problem is formulated. The primary stage in using systems dynamics modeling is to try to identify and understand the feedback loops of the system.

One of the existing methods for this is to draw causal loop diagrams. This stage is the first step in the operational process of systems dynamics modeling. The next stage in this modeling is to draw a stock-flow diagram. These diagrams aim is to show the relationships between the model variables.

4.5.1. Drawing the causal loop diagram of the model

In order to draw the causal loop diagram of the model, the relationships from budget allocation to reaching the final profit have been shown in a diagram. This diagram shows only one level of the multi-level supply chain; the other levels operate according to the same diagram (Figure 9).

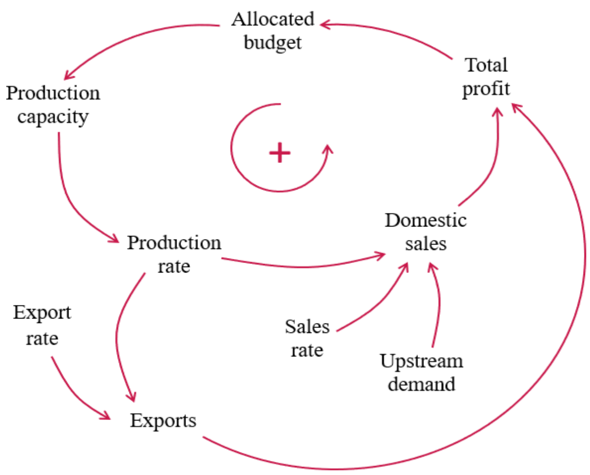

Figure 9. Causal loop diagram from budget allocation to profit achievement

This diagram invests the total profit obtained in increasing production capacity. Increasing production capacity leads to an increase in production rate, and with an increase in sales and exports, the total profit increases, and this process continues as a positive cycle. In the next diagram, five levels of the steel supply chain are visible (Figure 10). This diagram shows the relationship between the different levels of the multi-level supply chain.

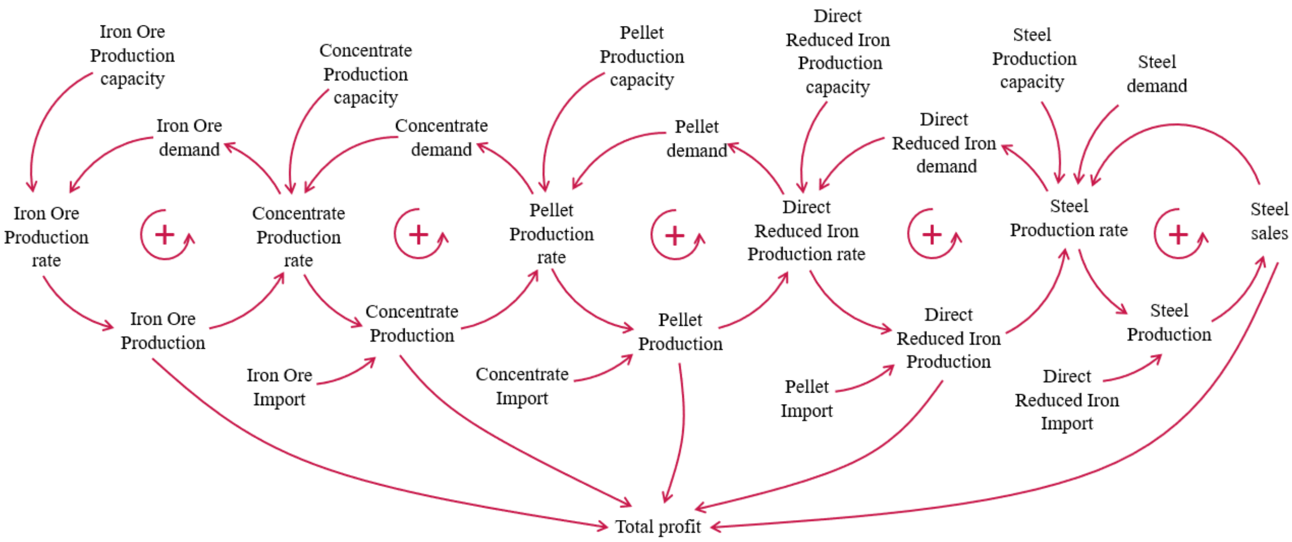

Figure 10. Causal loop diagram of the relationship between different parts of a multi-level supply chain

This diagram shows that the production capacity and production rate of upstream products influence the demand for downstream products. The diagram also illustrates the impact of imports within the supply chain. Each level exhibits a positive reinforcing cycle.

4.5.2. Drawing the stock-flow diagram

In order to draw the stock-flow diagram, all system variables must be identified, and the model boundaries must be clearly defined. State variables represent the accumulations within the system that indicate its current state, and the information from these variables informs decision-making and actions. Flow variables represent the rates of change of the state variables.

The stock-flow model was created using AnyLogic software. For simplicity, some variables are abbreviated, as shown in Table 4.

Table 4. Abbreviation of supply chain level names

Abbreviation	IO	IC	IP	DRI	CS
Word	Iron Ore	Iron Concentrate	Iron Pellet	ect Reduced Iron	Crude Steel

Figure 11 shows the stock-flow diagram for the first level of the multi-level steel supply chain, specifically for iron ore. This diagram includes as many variables as possible that impact the macro-level policies of this sector.

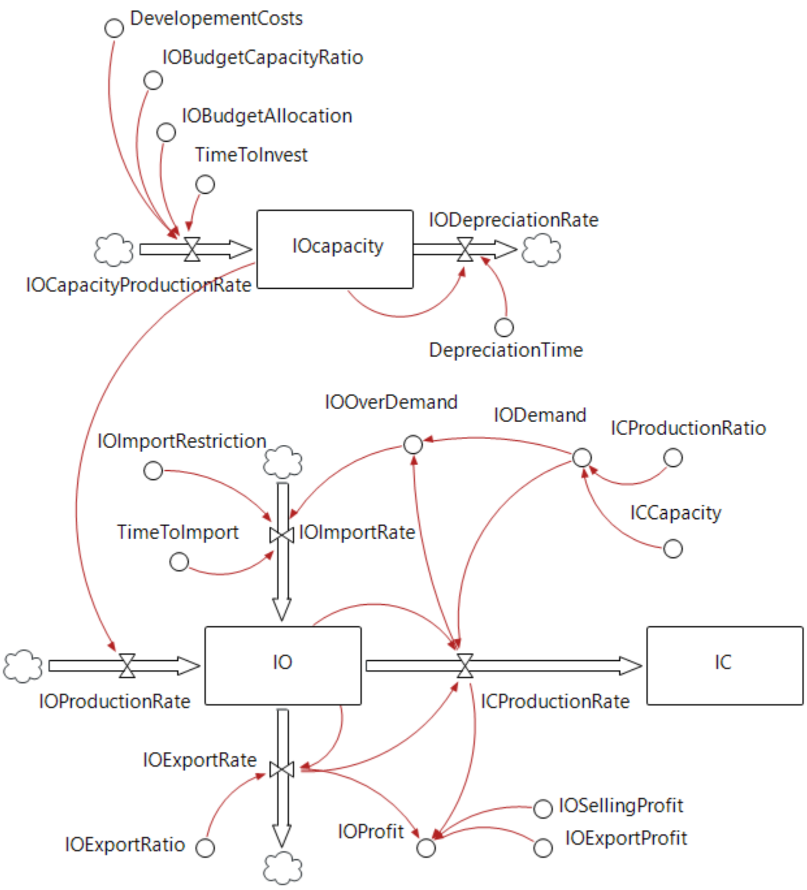

Figure 11. Stock-flow diagram of one level of a multi-level steel supply chain

In this diagram, two state variables are considered for the iron ore sector: the production capacity of iron ore (IOCapacity) and the accumulation of iron ore production (IO). The relationships between these variables and their impact on the system will be explained in detail. Figure 12 expands on the previous diagram by including all levels of the supply chain and their interrelationships. It presents the complete stock-flow diagram for a five-level steel supply chain.

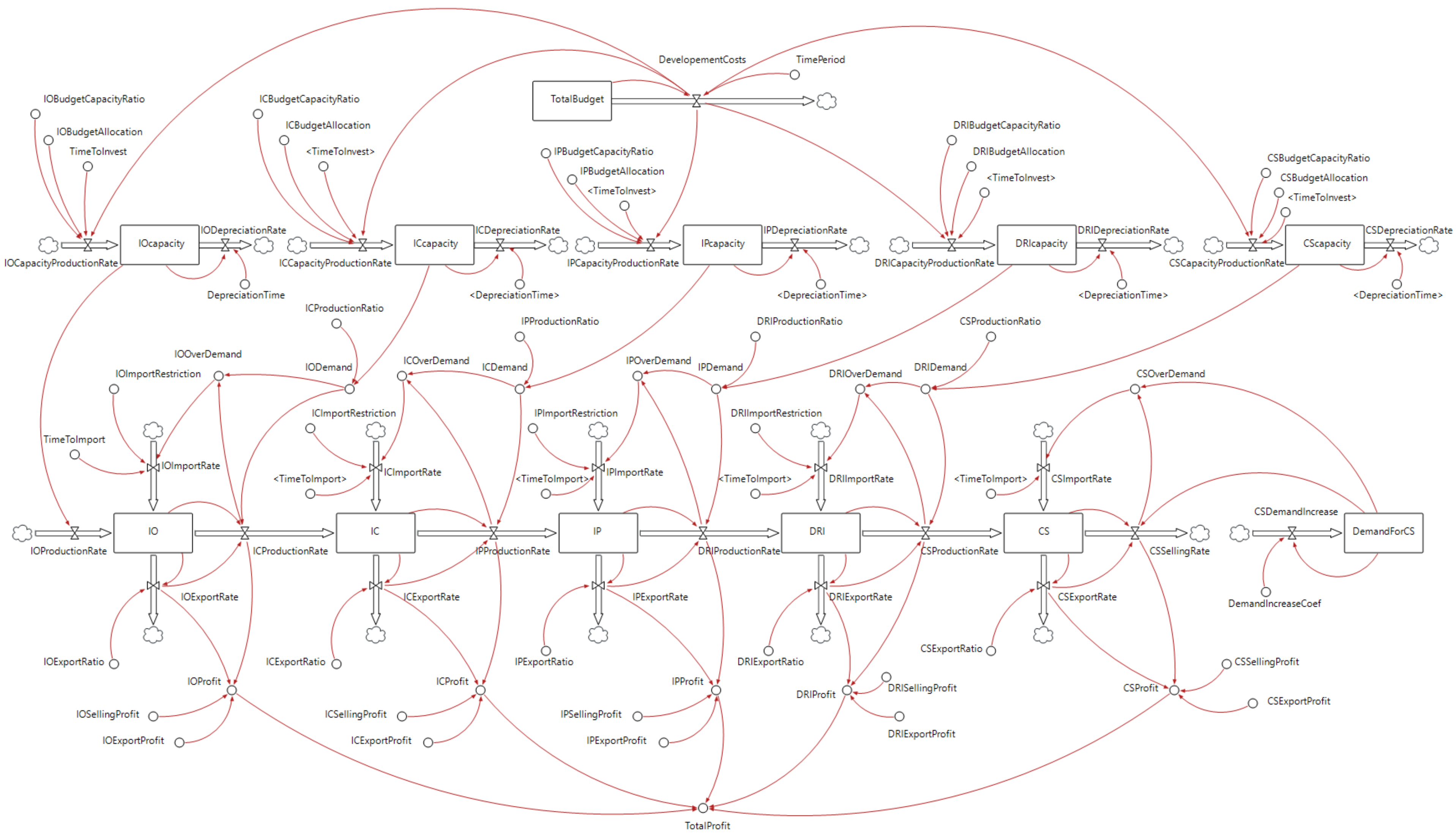

Figure 12. Stock-flow diagram of the problem for a five-level multi-level steel supply chain

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The next section will describe the mathematical relationships between the variables.

4.6. *Defining mathematical relationships*

At this stage, the mathematical relationships between the model variables are examined. These relationships are consistent across all five levels of the steel supply chain.

Development Costs = Total Budget/Time Period (2)

The development cost of production capacity is obtained by dividing the total allocated budget by the time required to consume this cost.

IO Capacity = INTEG (IO Capacity Production Rate - IO Depreciation Rate) (3)

The accumulation of iron ore capacity (IO) is equal to the integral of the production capacity creation rate minus the depreciation rate of production units. For the next levels of the supply chain, namely concentrate production (IC), pellet production (IP), direct reduced iron (DRI), and crude steel (CS), the calculations are done similarly. The initial values of these accumulations should also be determined based on the documents.

IO Capacity Production Rate = (IO Budget Allocation * Development Costs) / (IO Budget Capacity Ratio * Time to Invest) (4)

In order to obtain the iron ore capacity production rate, the percentage of the total development budget of the steel sector allocated to iron ore extraction must be multiplied by the total development costs. It should also be considered how much is needed to create one million tons of iron ore extraction capacity and the investment period..

IO Depreciation Rate = IO Capacity / Depreciation Time (5)

To calculate the depreciation rate, the accumulated iron ore capacity must be divided by its average depreciation time.

IO = INTEG (IO Import Rate + IO Production Rate - IO Export Rate - IC Production Rate) (6)

The accumulation of iron ore is calculated by integrating the sum of the inflow rates (i.e., the import rate of iron ore and the production rate of iron ore) minus the outflow rates (i.e., the export rate and the production rate of the next level product (concentrate)). The initial values of these accumulations should also be determined based on the documents.

IO Export Rate = IO * IO Export Ratio (7)

The export rate of iron ore is considered based on the policies of steel sector managers. In general, a large part of iron ore production should be used domestically to produce the next steel products in the supply chain, and all iron ore production should not be exported. Even though the profit from exporting iron ore may sometimes be higher than the that selling to domestic factories, legal restrictions must still be complied with.

CS Import Rate = Min (Import Restriction, IO Over Demand/Time to Import) (8)

The import rate of iron ore is determined based on the import restrictions. Given the domestic iron ore mineral resources, importing this product is not logical. Also, excess demand should affect iron ore imports. Therefore, if the demand for upstream units is higher than the iron ore extraction capacity, imports will be possible up to a certain limit.

IO Over Demand = Max (0, IO Demand - IC Production Rate) (9)

Excess demand for iron ore is obtained by comparing the demand for iron ore and the production rate of the upstream product of the supply chain (concentrate). If this value is negative, the excess demand becomes zero, and there will be no imports.

IO Production Rate = IO Capacity (10)

IC Production Rate = Min (IO – IO Export Rate, IO Demand) (11)

The iron ore extraction rate is equal to the accumulated iron ore capacity. This rate for the production of upstream products (concentrate) is equal to the demand for the production of the downstream product. Suppose the amount of the downstream product accumulation minus the amount exported is less than the domestic market demand. In that case, the production rate of the upstream product will be equal to the amount of the downstream product inventory in the market.

IO Demand = IC Capacity / IC Production Rate (12)

The demand for iron ore is determined by the upstream product, which is the concentrate and is obtained by dividing the production capacity of the upstream product by the ratio of concentrate production from one ton of iron ore.

CS Demand Increase = Demand for CS * Demand Increase Coefficient (13)

The rate of increase in the demand for crude steel (CS) is calculated by multiplying the existing demand inventory by the annual demand increase coefficient. The annual demand

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increase coefficient is determined based on the supply and demand of crude steel over the past ten years.

CS Selling Rate = Min (CS - CS Export Rate, Demand for CS) (14)

The sales rate of crude steel is calculated by comparing the demand for crude steel and the amount of crude steel inventory minus its export amount. If the demand for crude steel is less than its existing inventory, the sales rate will be equal to the demand, and if the demand is greater than the existing inventory, the sales will be equal to the inventory.

IO Profit = (IC Production Rate * IO Selling Profit) + (IO Export Rate * IO Export Profit) (15)

Total Profit = IO Profit + IC Profit + IP Profit + DRI Profit + CS Profit (16)

The profit from iron ore production includes domestic sales and exports. The total profit of the products is obtained by summing the profits from each level in Equation 16.

4.7. Running and validation the model

4.7.1. System warm-up time

Since simulation models do not have the same initial conditions as those in a real-world problem, a specific time is determined for system warm-up. In order to calculate the system warm-up time, it is recommended to plot a specific graph of the status of one or more system variables, and the approximate warm-up time can be determined from this graph. The system warm-up time is the time it takes for the simulated system to reach a relatively stable state. For this problem, to determine the warm-up time of the system, a graph was plotted to examine the behavior of the state variables of the production rate of three levels of the supply chain (pellet, direct reduced iron, and crude steel) over ten years (Figure 13).

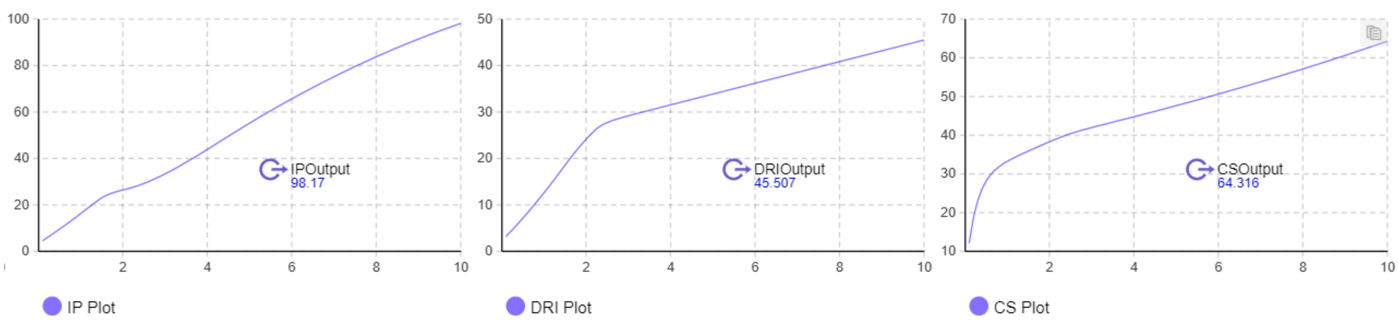

Figure 13. Analysis of variable behavior to determine system warm-up time

After examining these three diagrams, a warm-up time of two years was considered. All three diagrams reached a relatively stable state after about two years. The duration of the simulation run, excluding the system warm-up time, is 10 years. Therefore, the authors simulate for 12 years.

4.7.2. Model validation

In order to ensure that the model provides a sufficiently acceptable representation of the actual system, a validation process is carried out. In modeling each level of this supply chain, our effort has been to ensure that the outputs are consistent with the real-world problem environment and that the validation process has been carried out continuously. In this article also used several tests to check the validity of the model:

4.7.2.1. Boundary condition test

This test checks whether the model exhibits expected behavior under extreme conditions. These extreme conditions may not have occurred in the real world. In order to examine this test in this research, several state variables were examined regarding changes in the factors affecting their input rate. The variable that is being measured is the profit variable.

In this way, the authors want to examine if the authors significantly reduced the total budget of the supply chain by one thousandth from the second year. Then, what would be the trend of the total profit of the supply chain? As expected, the annual budget reduction of the supply chain shows its effect in all parts of the supply chain. For example, in Figure 14, changes in the budget reduction on iron ore production capacity can be seen. In cases where the annual budget is exhausted, the diagram becomes stepped.

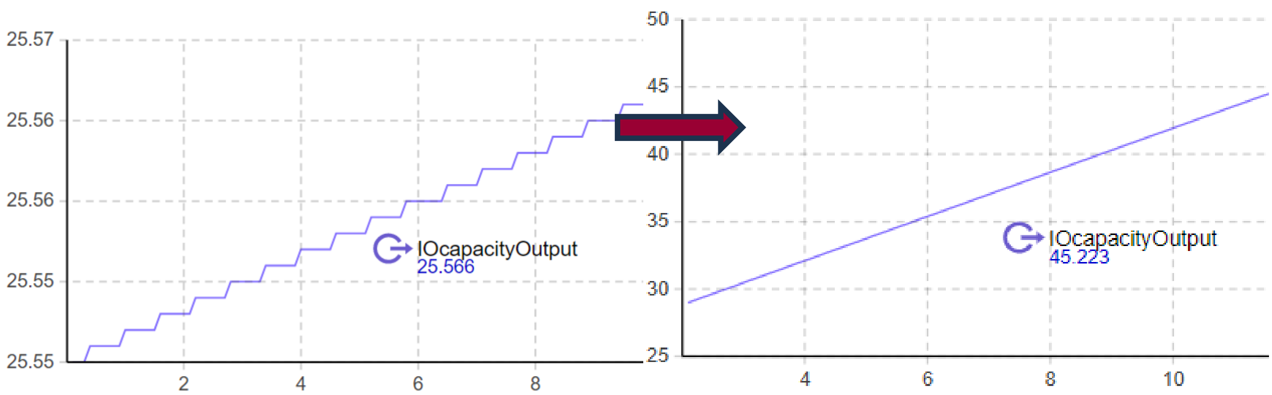

Figure 14. Examination of the behavior of the iron ore production capacity variable under extreme conditions

Ultimately, this stepped effect, after affecting the production rate and the state variable of the production amount of each level, affects the total profit (Figure 15).

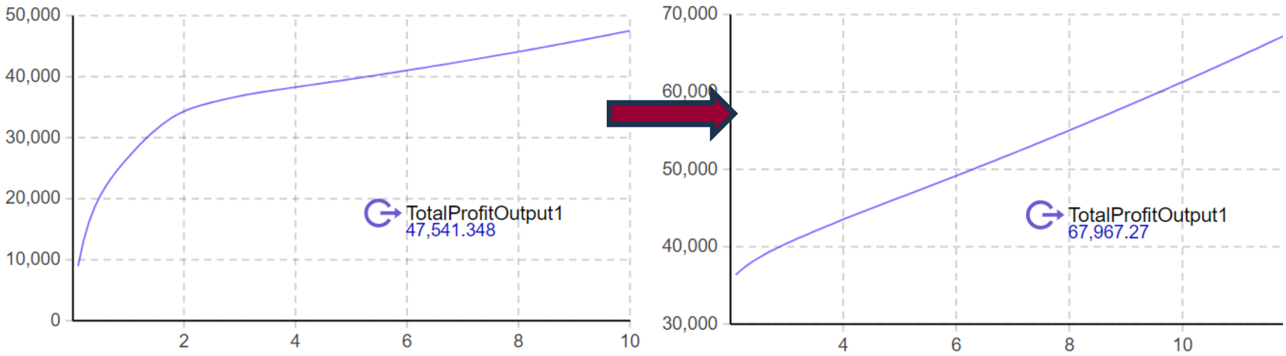

Figure 15. Analysis of the behavior of the total profit variable under extreme conditions

4.7.2.2. Reproduction behavior test

This test examines whether the model's initial conditions are equal to the conditions of the real world. If this match exists, the model can produce information similar to real systems. In order to examine this test, this article used reference diagrams to compare them with the diagrams produced by the model and measure their conformity. For this purpose, before simulating the future, the authors ran the model with data from the past years to compare its results with reality. According to Figure 16, the actual data of Iran's steel production from 2007 to 2022 is shown as a blue graph, and the values received from the simulation model are shown as a red graph. According to this diagram, the simulated values and the actual values have a reasonably good match.

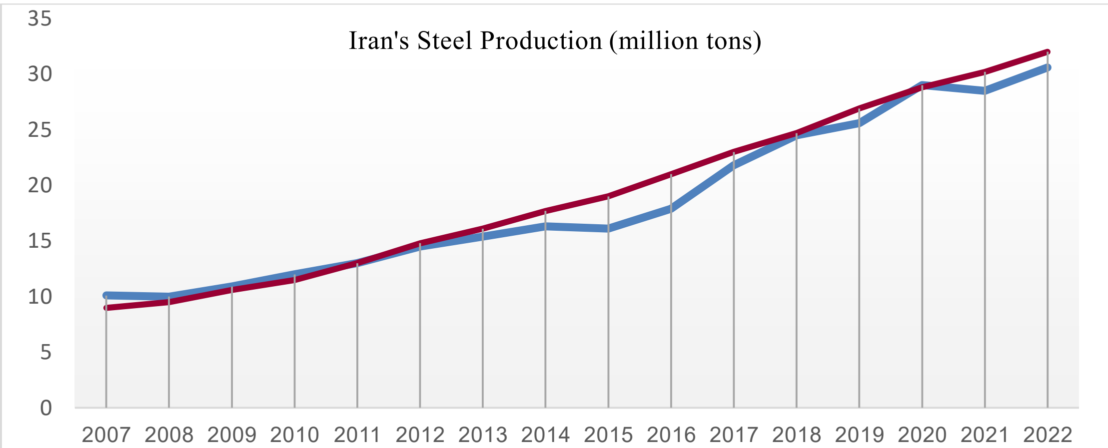

Figure 16. Comparison of Iran's crude steel production in reality and simulation

Also, in Figure 17, the actual data of Iran's iron ore extraction from 2007 to 2022 is shown as a blue graph, and the values received from the simulation model are shown as a red graph. This diagram also shows a relative match between the simulated and actual values.

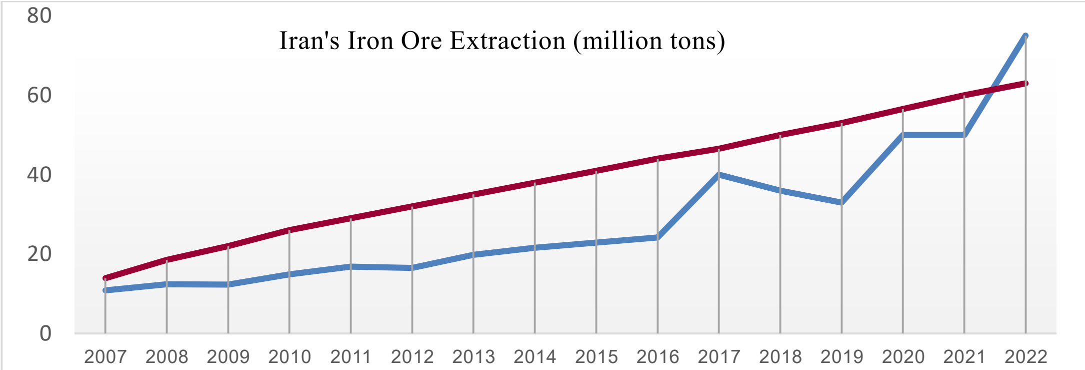

Figure 17. Comparison of Iran's iron ore extraction in reality and simulation

Another state variable examined in this section is the amount of Iran's steel exports. According to Figure 18, the actual data of Iran's steel exports from 2007 to 2022 is shown as a blue graph, and the values received from the simulation model are shown as a red graph. This diagram also shows a relative match between the simulated and actual values.

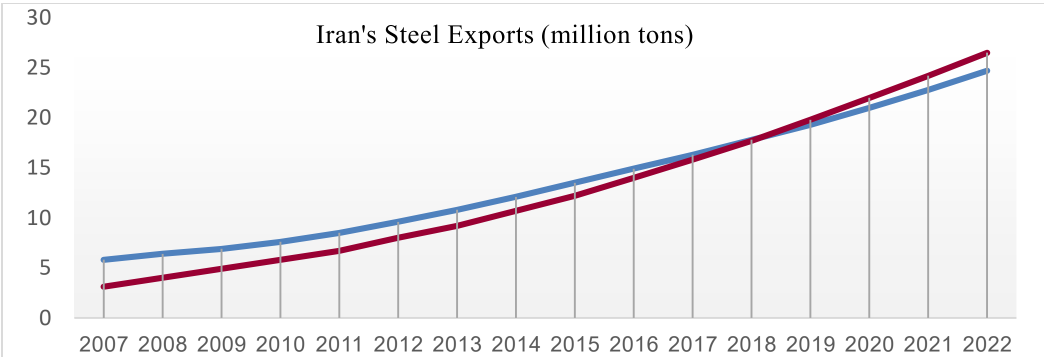

Figure 18. Comparison of Iran's steel exports in reality and simulation

4.7.2.3. Statistical validation methods

Important indicators that can be used to determine the degree of closeness of the simulated values to the actual values in the validation test of the system dynamics model and were used in this research include Root Mean Square Error (RMSE), Root Mean Square Percentage Error (RMSPE), Theil's Inequality Coefficient (U), and Theil's error decomposition. The statistical tests designed are shown in Table 5. For calculations, the base year was considered to be 2007.

Table 5. Statistical validation of the dynamic model

Variable	Root Mean Square Error (RMSE)	Root Mean Square Percentage Error (RMSPE)	Theil's Inequality Coefficient (U)	Theil's Error Decomposition		
				Correlation error	Variance error	Mean error
	The lower, the better	Value between zero and one hundred	Value between zero and one	The sum equals one		
IO Production	108.11	0.17	0.12	0.63	0.08	0.03
CS Production	522.18	0.17	0.12	0.63	0.08	0.03
CS Exports	4880.76	0.25	0.45	0.36	0.32	0.06
CS Sales	12920	0.18	0.11	0.63	0.01	0.10
Total Profit	10.62	0.30	0.03	0.38	0.31	0.03

The smaller the Theil index and the closer it is to zero, the closer the simulated numbers are to the actual numbers. Based on the investigations conducted in Table 5, the variables of the simulation model are close to the actual numbers, and the model's behavior, in terms of statistics, is reasonably close to the actual behaviors of the key variables of the problem. Therefore, the authors can run the model and receive the necessary outputs based on the policies. Model Execution

The model was run in AnyLogic software. The diagram of some of the model's accumulations and the total profit variable after running the model for 10 years is shown in Figure 19 and Figure 20.

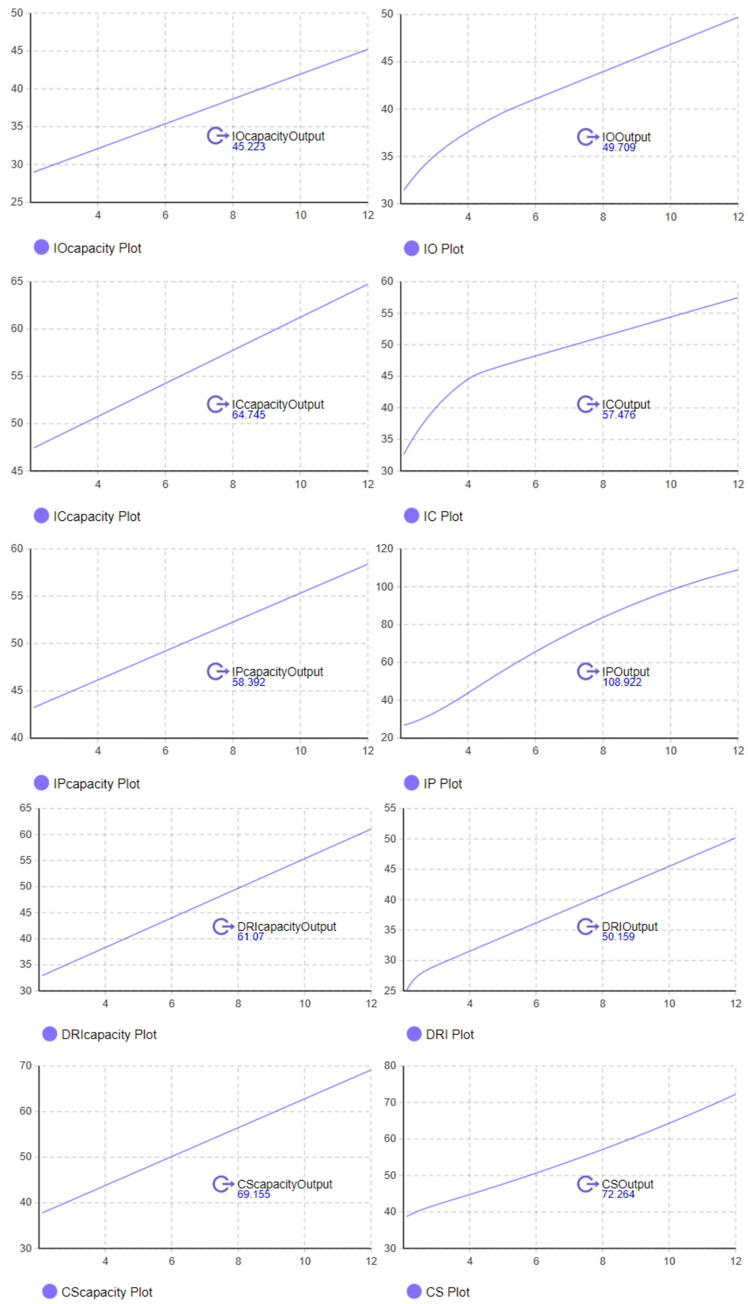

Figure 19. Model execution (Capacity and production of 5 levels of the supply chain)

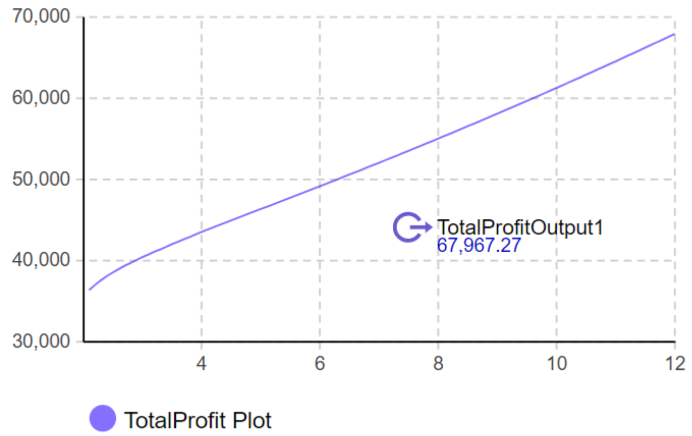

Figure 20. Model execution (Total profit)

4.8. Designing and conducting policies

The model's sensitivity to changes in some variables indicates the importance of those variables. Therefore, after running the model, the authors identified the more sensitive variables and tracked the effects of these changes made in the model by making changes to them. Since this research is looking to examine the macro policies of the supply chain, the authors select macro variables for sensitivity analysis. These variables are as follows:

- Total Budget
- Percentage of budget allocation for all five levels of the supply chain (Budget Allocation)
- Export limitation for all five levels of the supply chain (Export Ratio)

4.8.1. Sensitivity analysis of total budget allocated to the steel sector

Considering the budget allocated to create the capacity of the steel sector in Iran in the last 15 years, the total budget for the next 15 years is estimated to be 163831 million Tomans. With a 10% increase in the total allocated budget, the graph of changes in total profit will be shown in Figure 21.

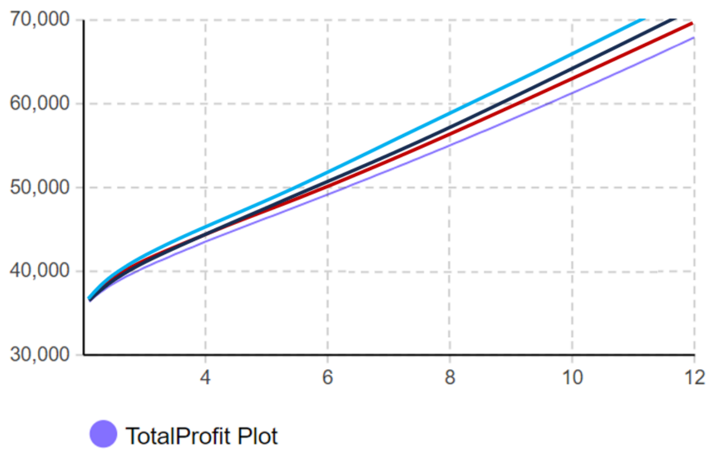

Figure 21. Sensitivity analysis of the total profit for an increase in the budget

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According to the diagram, the total profit change relative to the budget change is not very significant. Table 6 shows the percentage increase in total profit for an increase in the budget.

Table 6. Percentage increase in total profit for an increase in the budget

Allocated Budget	Percentage Increase	Total Profit	Percentage Increase
163831	-	67967	-
180214	10%	69624	2.43%
196597	10%	71275	2.37%
212980	10%	72901	2.28%

According to Table 6, increasing the budget will not be very profitable for this supply chain under the current conditions. However, focusing on one level of the supply chain to increase the budget may create higher profitability. Therefore, this article will analyze the sensitivity of the budget allocation percentage between different supply chain levels.

4.8.2. Sensitivity analysis of budget allocation to each level of the supply chain

In order to examine and analyze the sensitivity of the model to the percentage of budget allocation to each level of the supply chain, it has been added 8% to the budget allocation of each level, respectively, and 2% from each of the other levels. The results are according to Table 7.

Table 7. Amount of change in total profit for an increase in the budget of each level of the supply chain

Status	IO	IC	IP	DRI	CS	Total Profit	Percentage Increase
Initial State	15%	16%	14%	26%	29%	67967	-
Increase IO budget	23%	14%	12%	24%	27%	66736	-0.181%
Increase IC budget	13%	24%	12%	24%	27%	66669	-0.191%
Increase IP budget	13%	14%	22%	24%	27%	66770	-0.176%
Increase DRI budget	13%	14%	12%	34%	27%	68124	0.002%
Increase CS budget	13%	14%	12%	24%	37%	68293	0.005%
Increase DRI and CS budget	13%	14%	12%	29%	32%	69018	0.015%
Increase DRI and CS budget	11%	12%	10%	32%	35%	69769	0.026%

As shown in the table, only increasing the budget for direct reduced iron and crude steel can increase the overall profitability of the supply chain. The reason for this is the higher price of directly reduced iron and crude steel compared to the products of other levels of the steel supply chain. The more directly reduced iron and crude steel are produced, the more profitable it will be to import their raw materials from abroad and export the product abroad.

4.8.3. Sensitivity analysis of export limits at each level of the supply chain

In order to analyze the sensitivity of the model to export limits at each level of the supply chain, the export limit has been increased according to Table 8 (the initial state is calculated based on IMIDRO).

Table 8. Sensitivity analysis of export limits of each level of the supply chain

Status	IO	IC	IP	DRI	CS	Total Profit	Percentage Increase
Initial State	6.65%	3.86%	1.75%	3.33%	21.5%	67967	-
Increase IO limit	13.3%	3.86%	1.75%	3.33%	21.5%	67879	-
Decrease IO limit	3.32%	3.86%	1.75%	3.33%	21.5%	67911	-
Increase IC limit	6.65%	7.72%	1.75%	3.33%	21.5%	68042	0.001%
Decrease IC limit	6.65%	1.93%	1.75%	3.33%	21.5%	67870	-
Increase IP limit	6.65%	3.86%	3.5%	3.33%	21.5%	68174	0.003%
Decrease IP limit	6.65%	3.86%	0.87%	3.33%	21.5%	67845	-
Increase DRI limit	6.65%	3.86%	1.75%	6.67%	21.5%	68250	0.004%
Decrease DRI limit	6.65%	3.86%	1.75%	1.67%	21.5%	67831	-
Increase CS limit	6.65%	3.86%	1.75%	3.33%	43.0%	76931	0.13%
Decrease CS limit	6.65%	3.86%	1.75%	3.33%	10.7%	64734	-

Based on the results obtained, the export of crude steel is the most profitable part of Iran's steel supply chain. On the other hand, according to the analysis of the previous policy, increasing the budget for crude steel production also leads to higher chain profitability. The simultaneous analysis of these two policies shows that increasing the budget for investment in crude steel production can lead to increased production, and given that there is always the possibility of exporting crude steel, this investment will never fail.

4.9. Investigating the impact of industry 4.0 on the model

Since our model shows the macro level of the supply chain, it is impossible to examine the impact of Industry 4.0 at this level. For this reason, the impact of Industry 4.0 on improving the supply chain must first be calculated with another model that considers the intermediate level of the supply chain and then enters this impact into the dynamic model through a variable. For this reason, we use agent-based simulation for this part, according to Figure 22.

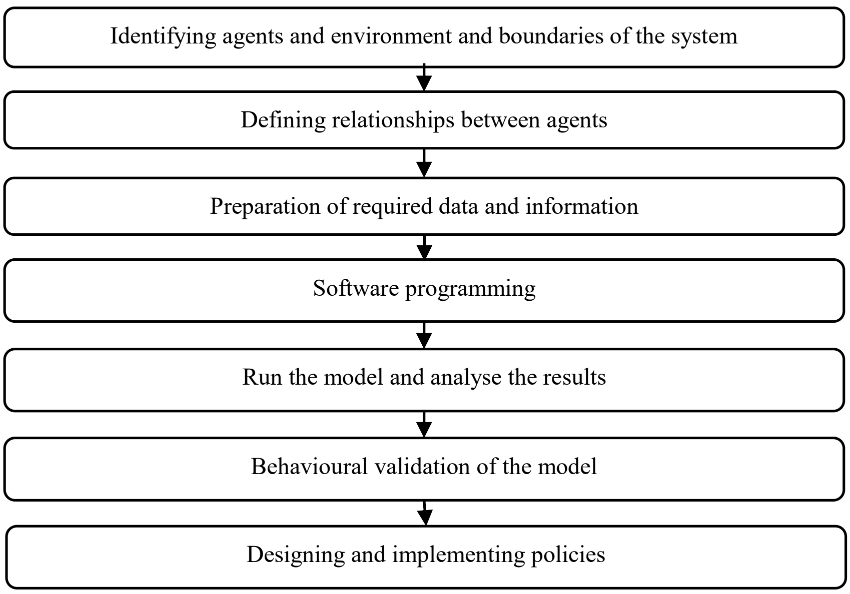


Figure 22. The stages of modeling by the agent-based method (Wang et al., 2021).

According to Figure 23, this article has six agents in this model, which respectively show the six levels of the steel supply chain.

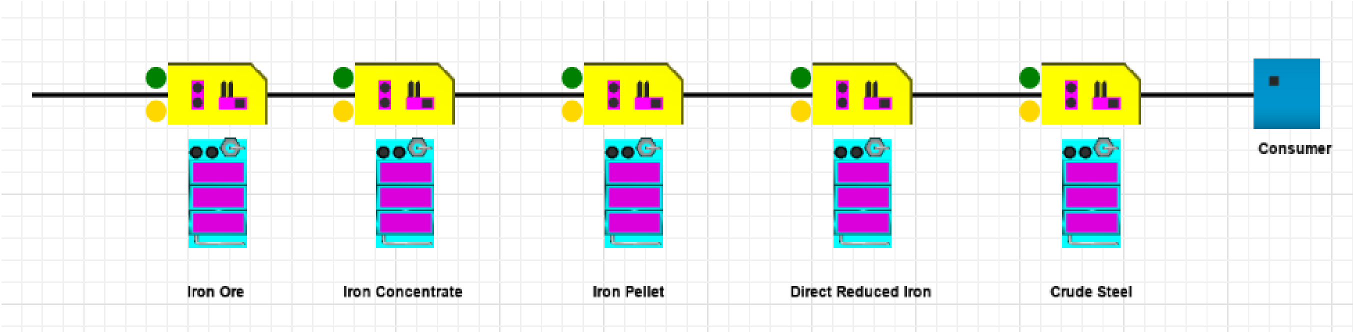


Figure 23. Agents of the levels of Iran's steel supply chain

The variables that were defined in this model in AnyLogic software for agents are as follows:

(1) Production rate
(2) The utilization rate of production capacity
(3) Inventory of raw materials
(4) Inventory of finished goods
(5) The quantity ordered to the supplier
(6) Transportation time between two production units
(7) The distance between two production units
(8) Customer demand
(9) Production capacity of each production unit
(10) Initial stock of raw materials in each production unit
(11) Minimum inventory level of raw materials

Each agent's location and production information of all active units of Iran's steel supply chain were introduced into the model as a CSV file.

In order to evaluate the performance of the model and examine how it works, the authors extract a key output. The authors selected the total distance traveled in Iran's steel supply chain and the total time spent to receive products from suppliers (from order to receipt) throughout the supply chain as the influential outputs of the model.

(1) Total distance traveled in the supply chain: This output shows the total distance that raw materials and finished products travel throughout the supply chain during production, transportation, and distribution.
(2) Total time spent to receive products: This output shows the total time it takes from the time customers receive products.

Examining both distance and time criteria simultaneously can determine the status of the supply chain for us.

Based on the data recorded in the model, the model has been run for ten years (from 1393 to 1402). The results are shown in Table 9.

Table 9. Simulation results of the annual distance traveled and waiting times

Number	Year	Total distance traveled (billion kilometers)	Total waiting times (million hours)
1	1393	220.225	3.1828
2	1394	225.147	3.2594
3	1395	226.657	3.2785
4	1396	227.843	3.2929
5	1397	230.346	3.3357
6	1398	233.478	3.3786
7	1399	235.619	3.3973
8	1400	238.135	3.4534
9	1401	241.476	3.4929
10	1402	243.145	3.5243

These distances are relatively large, indicating that efforts must be made to improve the efficiency of the supply chain. In order to examine policies, the authors will implement cases where the authors can implement Industry 4.0 in the model. Reducing the number of product movements and optimizing transportation routes reduce the distance traveled, saving time and costs. It can increase the competitiveness of Iran's steel supply chain in global markets.

In order to ensure the complete validity of the model, the dataset obtained from the model and the actual Iranian steel supply chain system were compared. Statistics from the Transportation Organization were used to obtain the actual model information in order to validate the model. For this purpose, the Kolmogorov-Smirnov test has been used the Kolmogorov-Smirnov test to measure the normality of the data, and then the analysis of variance and the F-test to determine the similarity of the variances and means of the two datasets. Finally, the T-test was used to examine the difference in means. A summary of the test results is shown in Table 10.

Table 10. Results of statistical tests

Parameter	**Value 1**			**Value 2**	
P-value	0.8436			0.5007	
D	0.139			0.1771	
K	0.4397			0.5602	
Skewness	0.06183			-0.02717	
Source	**DF**	**Sum of Square**	**Mean square**	**F Statistic**	**P-value**
Groups (between groups)	1	9.8	9.8	0.1583	0.6954
Error (within groups)	18	1114.0001	61.8889		
Total	19	1123.8001	59.1474		
Parameter	**Value**				
P-value	0.08859				
t	1.9091				

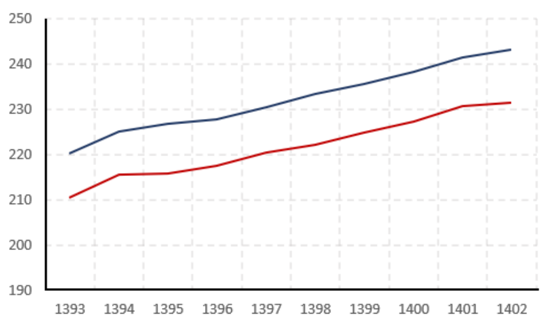
According to the tests, it can be claimed with 95% confidence that there is no significant statistical difference between the real system and the simulation model, and the created model is valid.

Then, this article examines the policies and sensitivity analysis of the supply chain model to changes in key parameters related to Industry 4.0. A policy that the authors can implement in this model by implementing the concepts of Industry 4.0 in Iran's steel supply chain is the horizontal integration of the supply chain. All production units operating at each chain level are somehow integrated by sharing their production on a common cloud platform. In this way, the production units at the next level can obtain the fastest raw materials from this cloud platform. In this case, suppliers and customers are not predetermined, and the nearest supplier is selected based on the distance that can deliver the product to the customer in the shortest time.

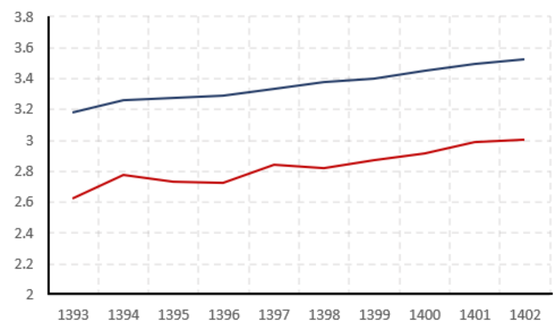
Table 11 shows the model's results before and after implementing the Industry 4.0 policy.Table 11. model results after implementing the Industry 4.0 policy

Number	Year	Total distance traveled (billion kilometers)		Percentage Increase	Total waiting times (million hours)		Percentage Increase
		Before I4.0	After I4.0		Before I4.0	After I4.0	
1	1393	220.225	210.365	4.48	3.1828	2.6248	17.53
2	1394	225.147	215.453	4.31	3.2594	2.7736	14.90
3	1395	226.657	215.756	4.81	3.2785	2.7347	16.59
4	1396	227.843	217.432	4.57	3.2929	2.7258	17.22
5	1397	230.346	220.496	4.28	3.3357	2.8439	14.74
6	1398	233.478	222.214	4.82	3.3786	2.8247	16.39
7	1399	235.619	224.934	4.53	3.3973	2.8736	15.42
8	1400	238.135	227.234	4.58	3.4534	2.9134	15.64
9	1401	241.476	230.763	4.44	3.4929	2.9878	14.46
10	1402	243.145	231.436	4.82	3.5243	3.0069	14.68

Changes in the number of distances traveled and amount of waiting times of the model after implementing the I4.0 policy are shown in Figure 24.



a: Changes in the amount of distances traveled



b: Changes in the amount of waiting times

Figure 24. Changes in the amount of distances traveled and amount of waiting times

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The results show that implementing this policy can reduce about 4.5% in the distance traveled and about 15% in waiting times in Iran's steel supply chain.

4.10. Connecting dynamic and agent-based simulations

In order to establish a connection between these two models and create a combined model, it's necessary to first calculate the percentage improvement in supply chain profitability within the agent-based model. The agent-based simulation results show that implementing Industry 4.0 can reduce the distance traveled by 4.5% and waiting times by 15%, so the annual cost savings from this performance improvement must be calculated.

According to information from the National Iranian Steel Company, transportation costs generally account for 15-25% of the total costs in Iran's steel supply chain. The authors assume this cost to be 20%. Therefore, with a 4.5% reduction in transportation costs, it can be estimated that approximately 0.9% of the total supply chain costs will decrease.

This study has used two intermediate variables to establish a connection between the two models (Figure 25).

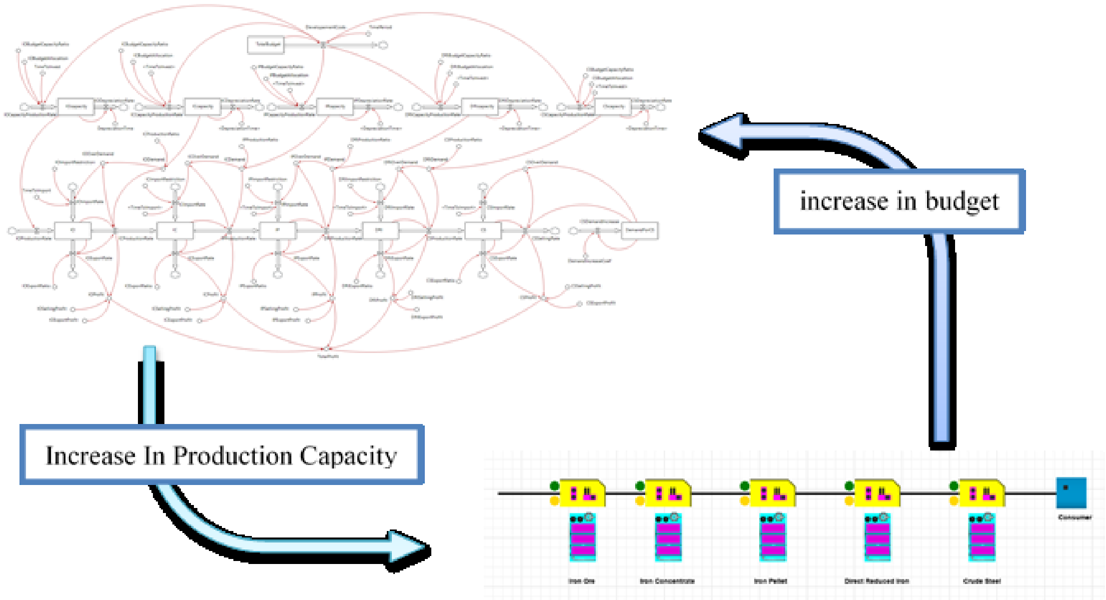


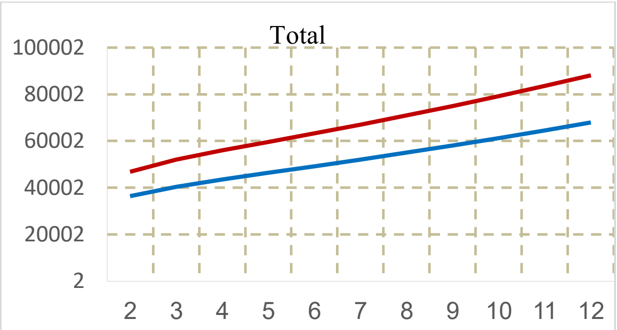
Figure 25. combined model

These intermediate variables increase the dynamic model's budget and the agent-based model's production capacity.The interplay between these two models is as follows: the profitability and cost reductions achieved in the agent-based model over a ten-year period are reflected in the dynamic model at the macro level and in overall policies. The impact of these improvements on overall profitability leads to increased investment and production capacity at the intermediate level.

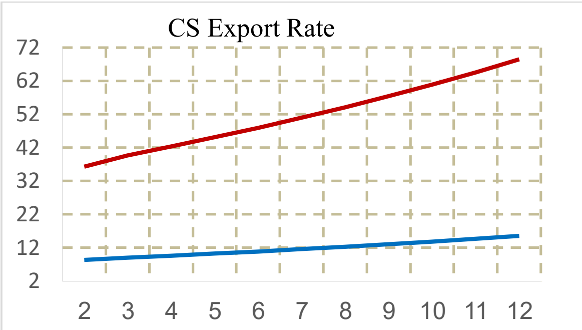
Based on the analysis conducted in both the dynamic and agent-based models, optimal policies must now be considered for the combined model.

Given the policies examined in the dynamic model, increasing the budget for direct reduced iron and crude steel can enhance the overall profitability of the supply chain. The study's analyses also indicate that exporting crude steel is the most profitable segment of Iran's steel supply chain. Therefore, in this section, the costs saved due to reduced distances resulting from Industry 4.0 can be invested in increasing the budget for investing in raw steel production. This investment can lead to increased raw steel production and, considering the constant possibility of exporting raw steel, will not fail.On the other hand, this increase in budget at the macro level leads to increased profitability, and the impact of this profit is reflected in the form of a variable increasing production capacity for raw steel producers.

The results of the dynamic model's profitability after ten years of model execution are shown in Figure 26 (a), and the increase in the export rate of raw steel is shown in Figure 26 (b). These figures demonstrate the successful impact of implementing Industry 4.0 in Iran's steel supply chain and the utilization of its material benefits in investment, increased production, and export of raw steel.



a: overall profitability of the supply chain



b: raw steel export rate over ten years

Figure 26. Impact of Industry 4.0 on the overall profitability of the supply chain and the raw steel export rate over ten years

5. Discussion and conclusion

Based on the system dynamic simulation and the agent-based analysis conducted on the Iranian steel supply chain data, it can be concluded that maintaining a balance between supply and demand at each stage of the supply chain plays a significant role in increasing efficiency and profitability. Increasing production capacity without considering demand, or vice versa, can lead to serious problems in the supply chain.

The model results showed that macro-level policies such as budget allocation, export limits, and support for investments in various parts of the supply chain directly impact the performance of this chain. Therefore, policymakers' decisions should be based on accurate analyses. Sensitivity analysis, considering the intermediate level of the supply chain and the application of Industry 4.0 to reduce costs, showed that increasing the budget and production capacity in the direct reduced iron and crude steel sectors has a greater impact on the overall profitability of the chain.

It indicates that investment in these sectors can yield higher returns than other sectors. Additionally, increasing the export limit for raw steel, especially compared to other products, can significantly impact the chain's overall profitability. It suggests that exporting crude steel can significantly increase revenue and foreign exchange for the country. Based on the results, several managerial recommendations can be made:

(1) Balanced Investment in Key Sectors: Managers should prioritize budget allocations and investments in the direct reduced iron and crude steel sectors, as these areas yield the highest returns. Allocating resources to these sectors can maximize profitability and ensure a stronger foundation for the entire supply chain.
(2) Focus on Export Strategies: The results suggest prioritizing crude steel exports over other products can significantly increase revenue. Decision-makers should consider adjusting export policies to capitalize on high-demand markets, potentially enhancing foreign exchange earnings.
(3) Adoption of Industry 4.0 Technologies: Embracing Industry 4.0, especially in areas such as digitalization, can aid in reducing operational costs and increasing supply chain flexibility.
(4) Risk Management and Policy Adjustments: Given the sensitivity of the supply chain to macro-level policies like export limits and budget allocations, policymakers need to maintain flexibility. Managers and policymakers should collaborate to develop adaptive policies that adjust to economic shifts and technological advancements.

Based on the analysis of this research, several limitations have been identified, along with recommendations for future research, as outlined below:

(1) Data Availability and Quality: A significant constraint in this study is the limited access to comprehensive data. Future research should aim for extensive datasets to enhance accuracy and detail.
(2) Generalizability: This study concentrates on Iran's steel supply chain, but the effectiveness of Industry 4.0 strategies can differ across regions and industries. Future research should consider replicating this study in varied national and industrial contexts to improve the generalizability of the findings.
(3) Long-term Impact Assessment: Due to the evolving nature of technology, it is crucial to assess the long-term impacts of Industry 4.0 on supply chains. Future studies could conduct longitudinal analyses to better understand how these technologies influence supply chain dynamics over time, providing a fuller picture of their impacts.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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