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Systems Dynamics Modelling of Gasoline Consumption in Iran

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ABSTRACT

This study presents a dynamic analysis of gasoline demand in Iran from 1978 to 2021, employing a system dynamics approach. A comprehensive model was developed to forecast gasoline consumption, incorporating key variables such as population, trip frequency, the number of gasoline-only vehicles, dual-fuel (gasoline-CNG) vehicles, the number of CNG stations, and the consumer price index (CPI). The model explicitly captures the complex and dynamic interrelationships among these variables, providing a nuanced understanding of the factors influencing gasoline consumption. Model validation was performed by comparing model predictions with actual gasoline consumption data from 2006 to 2021. The results demonstrate a satisfactory level of accuracy in simulating past gasoline consumption patterns. Following validation, the model was used to project gasoline demand from 2022 to 2031. In addition to a base scenario, three alternative scenarios were explored to assess the impact of different policy interventions aimed at reducing gasoline consumption. These scenarios involved increasing the number of dual-fuel vehicles, increasing the number of CNG stations, and a combined scenario incorporating both interventions. The projection results indicate that all three alternative scenarios lead to significant reductions in gasoline consumption compared to the base scenario. Notably, the scenario focusing on increasing the number of dual-fuel vehicles had the most substantial impact on reducing gasoline consumption. These findings underscore the importance of developing CNG infrastructure and promoting the adoption of dual-fuel vehicles as effective strategies for reducing gasoline dependence and managing fuel consumption in Iran. This research provides policymakers with a robust dynamic model for informed decision-making in fuel consumption management. Furthermore, the findings and methodology can be broadly applied to similar studies in other countries and related fields of energy and environmental research.

Keywords

Gasoline Consumption, Iran, Systems Dynamics, Energy Policy, CNG, Forecasting.

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1. Introduction

Iran faces a pressing challenge in managing its gasoline consumption, which remains among the highest globally and is increasingly unsustainable. Persistent growth in demand—driven by inefficient vehicles, an aging fleet, and extensive government subsidies—has placed mounting pressure on the energy sector. In 2024, national consumption reached 113 million liters per day, representing an 8% year-over-year increase ([Iran Chamber Newsroom, 2024](#)). This surge, coupled with limited refining capacity, has widened the gap between domestic production and demand, forcing greater reliance on imports and barter-based fuel trade.

Many studies have utilized econometric methods—primarily regression analyses—to explore the relationship between gasoline consumption and various economic factors such as price, income, and growth (e.g., [Al-Ghandoor et al., 2013](#); [An-loh, Botsas, and Monroe, 1985](#); [Bates and Kim, 2024](#); [Goetzke and Vance, 2021](#); [Kilian and Zhou, 2024](#); [Lee and Olasehinde-Williams, 2021](#); [Rogat and Sterner, 1998](#); [Sapnken et al., 2018](#)). Among these, [Mikayilov et al. \(2020a\)](#) specifically examined gasoline price elasticity in fuel-subsidizing economies, offering insights that are especially relevant to Iran's context. These approaches often focus on price elasticity and other statistical relationships. Recently, machine learning techniques, including deep learning, have been increasingly applied for forecasting gasoline consumption ([Bayat, Davoodi, and Rezaei, 2023](#); [Ceylan, Akbulut, and Baytürk, 2024](#); [Yang et al., 2022](#); [Yu et al., 2021](#)). However, while these methods provide valuable insights, they may lack in-depth explanatory power regarding causal mechanisms.

In contrast, system dynamics modeling offers a holistic approach by explicitly representing feedback loops and interactions among variables, providing deeper insights into the dynamic behavior of gasoline consumption systems over time. This approach has been effectively applied in previous studies to model urban air pollution ([Vafa-Arani et al., 2014](#)) and gasoline demand ([Zareayan Mazrae Khosro and Shakouri Ganjavi, 2016](#)). Unlike econometric models that primarily analyze static relationships or machine learning methods focused on prediction, system dynamics can elucidate how factors such as vehicle efficiency, government policies, and infrastructure developments interact to influence gasoline demand.

Unlike prior models that isolate econometric or predictive frameworks, this study offers a dynamic system model tailored to Iran's fuel infrastructure, incorporating trip frequency, CPI, and policy simulations. The innovation lies in the causal structuring and integration of policy feedback, especially in modeling the adoption of hybrid vehicles and the accessibility of CNG.

This study aims to investigate the various factors influencing gasoline consumption in Iran through a dynamic modeling approach. The unique challenges within the Iranian context—including significant energy subsidies, fluctuating gasoline prices, and an increasing reliance on personal vehicles—complicate the dynamics of fuel demand. Prior research has established links between travel behavior and fuel consumption, but a comprehensive analysis that effectively integrates these multiple influencing factors remains limited.

To address this gap, the study poses the following research questions:

- What are the key factors influencing gasoline consumption in Iran?
- How do economic conditions, such as GDP and inflation, affect gasoline demand?
- What role do vehicle types—specifically dual-fuel and hybrid vehicles—play in shaping gasoline consumption patterns?
- How effective are policy interventions aimed at promoting alternative fuels and reducing gasoline dependency?

Based on these questions, the study hypothesizes that increased trip frequency will correlate with higher gasoline consumption and that the expansion of CNG infrastructure and the adoption of dual-fuel vehicles will significantly mitigate gasoline demand.

The findings of this study will provide valuable insights into the determinants of gasoline consumption in Iran, offering a robust framework for policymakers to develop targeted interventions that promote sustainable energy use and reduce environmental impacts. The paper is structured as follows: Section 1 provides the background on Iran's gasoline consumption challenges and justifies the use of system dynamics modeling. Section 2 details the methodology, including the model structure, data sources, and calibration/validation techniques. Section 3 presents the results from the simulation experiments, analyzing the impacts of key factors and policy scenarios. Section 4 discusses the policy implications derived from the model's outputs, offering recommendations for sustainable transportation strategies in Iran. Finally, Section 5 concludes the study, highlighting its contributions, limitations, and potential avenues for future research.

2. Literature review

2.1. *Methodological approaches to gasoline consumption modeling*

Numerous studies have employed diverse methodologies to model and forecast gasoline consumption, each with its strengths and limitations. Traditional econometric techniques—such as linear regression—have been widely used to establish relationships between gasoline demand and variables like price, income, and vehicle ownership (e.g., [Sapnken et al., 2018](#); [Al-](#)

Ghandoor et al., 2013; An-loh et al., 1985; Rogat and Sterner, 1998). However, these approaches often assume linearity and struggle to account for the system's dynamic and multifaceted nature (Chang, 2016).

More advanced econometric frameworks, including correlated random coefficient models (Bates and Kim, 2024) and time-varying coefficient approaches (Lee and Olasehinde-Williams, 2021), have been adopted to address these shortcomings, offering improved estimation of demand elasticities. Mikayilov et al. (2020b) analyzed price and income elasticities in petroleum-dependent economies, providing insights into their temporal fluctuations—an issue particularly relevant to Iran's subsidy-laden fuel market. Other studies have revealed that elasticity estimates can vary significantly across different national and socioeconomic contexts (Goetzke and Vance, 2021; Kilian and Zhou, 2024).

In parallel, machine learning (ML) algorithms have emerged as powerful forecasting tools, capable of capturing non-linear patterns and complex interdependencies within consumption data (e.g., Ayyildiz and Murat, 2024; Ceylan et al., 2024; Bayat et al., 2023; Yang et al., 2022; Yu et al., 2021). For instance, Yang et al. (2022) and Bayat et al. (2023) demonstrated the efficacy of ML models—particularly deep learning and big data integration—in short-term fuel consumption prediction using multidimensional inputs and on-board diagnostics. Despite their predictive strength, such models often operate as "black boxes," limiting interpretability and hinders their suitability for policy analysis, where causal understanding is crucial. More recently, hybrid approaches have emerged that integrate data mining techniques with system dynamics to model energy policies and fuel demand (Roudbaraki et al., 2025).

In contrast to these predominantly static or predictive approaches, system dynamics modeling offers a unique framework for analyzing the complex dynamics of gasoline consumption (Akbari et al., 2020; Shamsapour et al., 2021; Zareayan Mazrae Khosro and Shakouri Ganjavi, 2016; Vafa-Arani et al., 2014; Mosleh Shirazi and Sotodeh, 2015). This approach explicitly represents the feedback loops and interactions between various factors, allowing for a more comprehensive understanding of the system's behavior over time. Studies have used system dynamics to model the impact of policies such as fuel subsidies (Mosleh Shirazi and Sotodeh, 2015) and vehicle hybridization (Norouzi et al., 2022) on energy consumption and emissions. Hourri Jafari and Baratimalayeri (2008) highlighted the crisis in Iran's transportation sector, setting the stage for a system dynamics approach capable of analyzing such a complex problem. While some studies have explored specific aspects using system dynamics, this research proposes a comprehensive model capturing a wider range of influential factors, offering

potentially richer insights for policymaking in the context of Iran's specific challenges, including its unique energy policy landscape (Raei et al., 2024; Saryazdi and Tavangar, 2023; Samavi et al., 2024; Ansarinassab and Manzari Tavakoli, 2020). The model will build upon the foundation laid by previous system dynamics work, addressing the gaps in understanding the complete interplay of factors influencing Iranian gasoline consumption. Moshiri (2020) and Moshiri and Aliyev (2017) provide relevant context on consumer behavior and rebound effects, which will be considered in the development of the model. Salimi et al. (2022) provide valuable insights into gasoline supply and demand modeling, informing the structure of the proposed system dynamics model. Heidari et al. (2023) and Pourmatin et al. (2024) demonstrate the applicability of system dynamics in modeling related aspects, such as CO₂ emissions and low-carbon vehicle transitions, thereby further supporting the chosen methodology. Finally, the work by Ghoddusi et al. (2019) on foreign exchange shocks provides an additional important context for the Iranian case.

2.2. Challenges of gasoline consumption in Iran and their policy implications

Gasoline consumption in Iran presents significant challenges that impact the economy, environment, and social stability. The consumption breakdown reveals that 61% of gasoline is used by passenger cars, 8% by taxis, 21% by vans, 4% by trucks and light trucks, and 6% by motorcycles, indicating the dominance of personal vehicles in overall consumption patterns.

Historically, Iran's refining capacity has fluctuated, reaching a low of 751,000 barrels per day during the Iran-Iraq War and climbing to over 2.3 million barrels per day by December 2019, reflecting substantial investments in new and upgraded refineries. Despite this increased capacity, current gasoline consumption levels continue to pose significant challenges as illustrated in Figure 1.

Iran's per capita energy consumption, particularly of gasoline, significantly exceeds the global average. Coupled with low energy prices and substantial energy subsidies—approximately 90% of hidden subsidies reported in 2020—Iran is one of the leading international providers of energy subsidies. Notably, its gasoline consumption is about ten times higher than that of Turkey, despite similar population sizes.

Historically, a positive correlation has existed between population growth, increasing motor vehicle ownership, and gasoline consumption. Until 2006, gasoline consumption exhibited a continuous upward trend. The introduction of Compressed Natural Gas (CNG) as a gasoline

substitute in 2004 and the implementation of fuel rationing through the "fuel card" system in 2006 led to a temporary decline in gasoline consumption, which lasted until 2011.

However, this downward trend reversed in 2011 with the removal of gasoline rationing and the implementation of a single-price system in 2015. This resurgence is largely attributed to Iran's growing young population and the subsequent increase in vehicle ownership, with the number of passenger vehicles rising from approximately 11,179,681 in 2011 to nearly 24 million by 2021. Although the reintroduction of rationing in 2019 temporarily curtailed consumption for a single year, the long-term trajectory remains concerning.

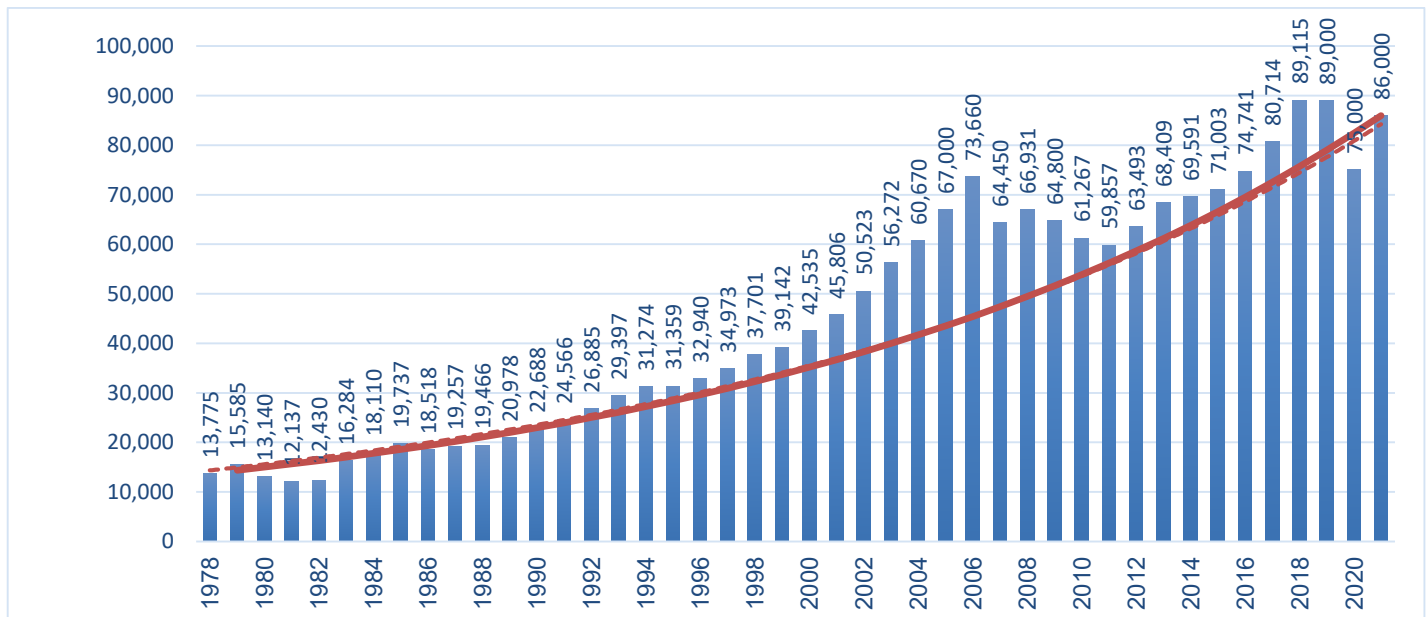


Figure 1. Daily gasoline consumption (thousands of liters) 1978-2021.

2.3. The multifaceted nature of gasoline consumption

As presented in Table 1, the adverse consequences of excessive gasoline consumption in Iran span environmental, economic, and social domains. This multidimensional challenge highlights the need for coordinated interventions, including strengthening fuel efficiency standards, investing in public transportation infrastructure, expanding access to CNG and electric vehicles, and implementing gradual fuel pricing reforms.

Table 1. Impacts of gasoline consumption and policy responses

Impact domain	Negative effects	Policy interventions	System dynamics feedback loop
Air pollution and public health	Elevated CO ₂ and PM emissions contribute to the development of respiratory and cardiovascular diseases, particularly in urban areas.	Strengthen fuel efficiency standards; phase out old vehicles; encourage electric and hybrid cars.	Pollution ↑ → Healthcare costs ↑ → Budget pressure ↑ → Subsidy reform → Fuel consumption ↓
Economic burden	Budget pressure from subsidies (>\$50 billion/year), fuel smuggling, and underpricing of gasoline.	Implement gradual fuel pricing reforms; redesign subsidies; allocate smart fuel quotas per person.	Subsidies ↑ → Consumption ↑ → Budget deficit ↑ → Policy reform → Price adjustment → Behavior change
Social impacts	Price volatility can spark public protests and worsen inequality; low-income households face disproportionate burdens.	Provide targeted cash transfers; increase subsidy transparency; design inclusive fuel policies.	Price shocks → Social unrest ↑ → Compensatory policies → Infrastructure development → Demand shift
Environmental degradation	Soil and water contamination from poor-quality fuels; loss of biodiversity and increasing climate risks.	Expand clean fuel infrastructure (CNG, EV); prohibit harmful additives; upgrade refinery standards.	Fossil fuel use ↑ → Environmental damage ↑ → Restoration costs ↑ → Environmental taxes ↑ → Demand ↓

The table further highlights how these policies interact with system dynamics feedback loops, offering a comprehensive framework for mitigating fuel demand through strategic policy design.

2.4. Determinants of gasoline demand

The factors influencing gasoline demand in Iran are complex and interconnected, spanning economic, social, environmental, technological, political, cultural, and demographic aspects. Table 2 summarizes the multidimensional factors influencing gasoline consumption, adapted from comparative fuel demand studies ([Newman and Kenworthy, 2021](#); [Romero et al., 2024](#)).

Table 2. Determinants of gasoline consumption

Factor category	Sub-Factor	Impact on gasoline consumption	Description
Economic factors	Gasoline Price (Government-set)	Positive (subsidies); Negative (higher prices)	Consumer behavior is directly impacted; subsidies increase consumption.
	Per Capita Income	Positive	Higher income leads to more vehicles and higher consumption
	Fuel Taxes	Negative (if effectively implemented)	Influences consumption, effectiveness varies with tax levels and enforcement.
Social factors	Number of Vehicles	Positive	Directly proportional to gasoline consumption.
	Public Transportation	Negative	Reduces reliance on personal vehicles and fuel use.
	Consumer Behavior (Fuel Efficiency Attitudes)	Positive (if fuel-efficient)	Fuel efficiency habits and attitudes significantly influence consumption.
Environmental factors	Environmental Concerns	Negative	Growing awareness promotes fuel-efficient choices and alternatives
	Climate Change Policies	Negative	Government regulations indirectly reduce gasoline demand.
Technological factors	Vehicle Technology (Fuel Efficiency)	Negative	Fuel-efficient vehicles reduce gasoline demand.
	Fuel Efficiency Improvements	Negative	Technological advancements lower consumption rates
	Consumption Management Software/Apps	Negative	Positive influence on consumer behavior.
Political factors	Energy Policies	Varies (depending on policy)	Significantly impacts consumption patterns.
	Regulations (Fuel Production and Consumption)	Varies (depending on regulation)	Influences fuel production, consumption, and renewable energy use.
	Financial Incentives (Fuel-Efficient Vehicles)	Negative	Subsidies encourage fuel-efficient choices
Cultural factors	Cultural and Social Habits	Varies (depending on habits)	Travel patterns affect gasoline demand.
	Desire for Modernization	Positive	Preference for new vehicles increases consumption.
Demographic factors	Population Size and Distribution	Positive	Larger populations consume more gasoline
	Age and Gender	Varies (depending on demographic)	Consumption varies across different groups.
Other factors	Availability of Alternative Fuels (e.g., CNG)	Negative	Increased availability reduces gasoline demand
	Access to Fuel Stations (Alternative Fuels)	Negative	Convenient access promotes alternative fuel use.

3. Methodology

3.1. Conceptualization of the gasoline consumption dynamic system

3.1.1. Model components: Stocks, flows, and auxiliary variables

The research variables are detailed in the following table:

Table 3. Research variables

No.	Variable name	Period available	Min	Max	Growth rate	Variable type
1	Petrol consumption	1957-2021	12137	89115	0.0435	Flow
2	Petrol production	1957-2021	15187	106000	0.0473	Flow
3	Petrol price	1957-2021	1	1500	0.1854	Stock
4	Number of petrol stations	1976-2021	995	3937	0.056559	Stock
5	Number of petrol cars	1985-2021	6019008	19415351	0.081204941	Stock
6	Petrol export	1985-2021	0	1.9		Flow
7	Petrol import	1957-2021	0	27.5		Flow
8	Consumable petrol	1957-2021	12743	93370	0.043514186	Stock
9	CNG Consumption	1983-2021	0.4	23.32	0.2702	Flow
10	CNG Production		0.44	25.652	0.270173	Flow
11	CNG Price	1984-2021	80	657	0.13186	Stock
12	Number of CNG stations	1957-2021	3	2500	0.1693	Stock
13	Number of hybrid cars	NA	NA	NA	NA	Stock
14	Traffic congestion index	1957-2021	0.26	113.35	NA	Auxiliary
15	Welfare index	1957-2021	0.42	0.89	NA	Auxiliary

Table 3 compiles key variables influencing gasoline and CNG consumption, based on national datasets and previous modeling frameworks (Salimi et al., 2022; Heidari et al., 2023).

3.1.2. Causal loop diagram

A causal loop diagram (Figure 2) visually represents the relationships between variables, using "+" to denote positive relationships and "-" to denote negative relationships.

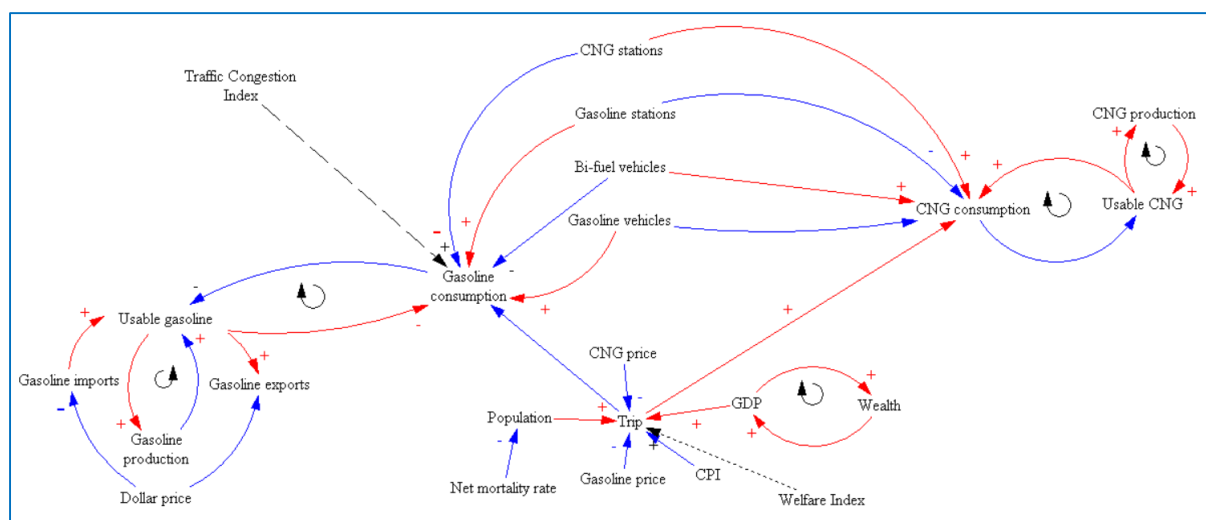


Figure 2. Causal loop diagram of gasoline consumption system

To enhance model realism, qualitative inputs such as traffic congestion and welfare indicators were incorporated as auxiliary variables that impact trip frequency and fuel choice (Allen and Arkolakis, 2022; Nitoiu et al., 2025).

3.1.3. Stock and flow diagram

This diagram (Figure 3) translates the causal loop diagram into a stock and flow model, focusing on the key variables of gasoline consumption, CNG consumption, and the number of trips. Trips are treated as a constant, influenced by population, GDP, CPI, gasoline price, and CNG price. Policy parameters (Policy Parameter 1 and 2) are introduced to model policy interventions on the number of hybrid cars and CNG stations.

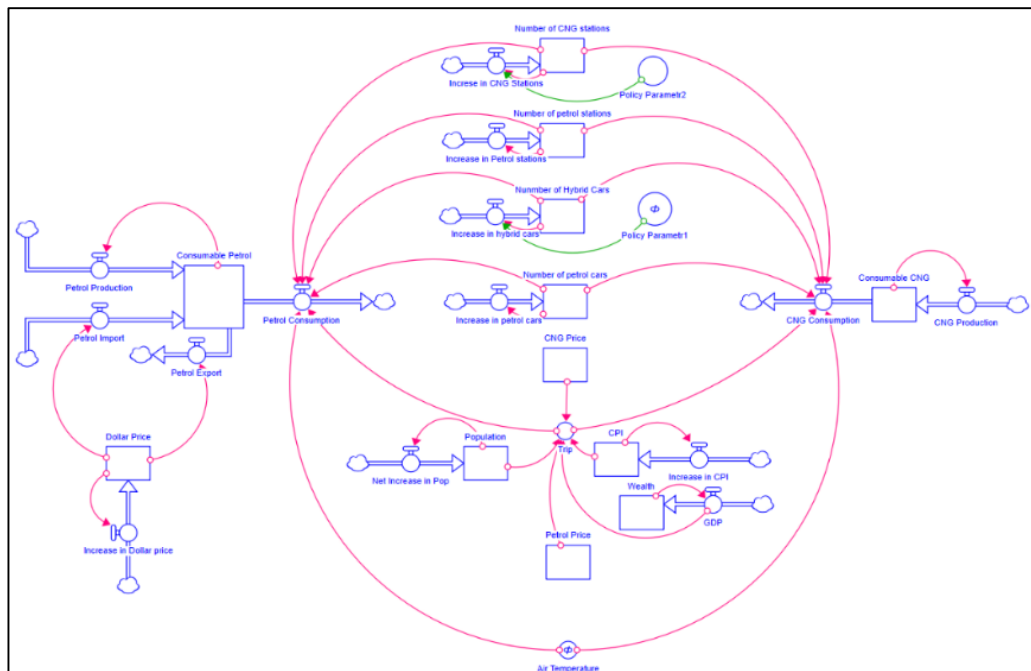


Figure 3. Stock and flow diagram of gasoline consumption

3.1.4. Regression analysis of trips and fuel consumption

In this section, we employ regression analysis using EViews to examine the relationships between various factors influencing trips and fuel consumption in Iran. Three distinct regression models were developed: one to predict the number of trips, another to predict gasoline consumption, and a third to predict CNG consumption. The results, including estimated coefficients and p-values, are presented in Tables 4, 5, and 6. Notably, we observe a strong positive correlation between trips and gasoline consumption, with a p-value of 0.000, indicating statistical significance.

The findings from each regression model are summarized below:

1. Trips model (Table 4)

This model predicts the number of trips based on several variables, including population, Consumer Price Index (CPI), Gross Domestic Product (GDP), gasoline prices, CNG prices, and trips from the prior period.

Table 4. Regression analysis of trips model

Variable	Coefficient	p-value	Interpretation
Population	1.673	0.0169	Positive and statistically significant; higher population increases the number of trips.
CPI	-2.103	0.0540	Negative and marginally significant; higher CPI may slightly reduce trips.
GDP	-0.000271	0.6429	No statistically significant relationship.
Gasoline Price	-6.3962	0.6782	No statistically significant relationship.
CNG Price	-10.168	0.2210	No statistically significant relationship.
Previous Period Trips	0.3249	0.3769	No statistically significant relationship.

2. Gasoline consumption model (Table 5)

This model evaluates gasoline consumption based on the number of CNG stations, dual-fuel vehicles, gasoline-only vehicles, gasoline stations, the number of trips, and previous gasoline consumption.

Table 5. Regression analysis of gasoline consumption

Variable	Coefficient	p-value	Interpretation
CNG Stations	-1.9757	0.0043	A negative and statistically significant correlation exists between the increase in CNG stations and reduced gasoline consumption.
Dual-Fuel Vehicles	-1.840	0.0302	Negative and statistically significant; a higher number of dual-fuel vehicles corresponds to lower gasoline consumption.
Gasoline-Only Vehicles	0.830	0.0580	Positive and marginally significant; an increase in gasoline-only vehicles leads to higher gasoline consumption.
Gasoline Stations	-0.3020	0.5165	No statistically significant relationship.
Trips	1.015	0.0000	Positive and highly statistically significant; increased trips lead to greater gasoline consumption.
Previous Period Gasoline Consumption	-0.0012	0.9627	No statistically significant relationship.

3. CNG consumption model (Table 6)

This model focuses on predicting CNG consumption, taking into account the number of CNG stations, dual-fuel vehicles, gasoline-only vehicles, gasoline stations, and the frequency of trips.

Table 6. Regression of CNG consumption

Variable	Coefficient	p-value	Interpretation
CNG Stations	0.0097	0.0000	Positive and highly statistically significant; more CNG stations lead to increased CNG consumption.
Dual-Fuel Vehicles	2.003	0.0412	Positive and statistically significant; higher numbers of dual-fuel vehicles correlate with increased CNG consumption.
Gasoline-Only Vehicles	-3.26e-7	0.3066	No statistically significant relationship.
Gasoline Stations	0.0019	0.1062	No statistically significant relationship.
Trips	8.03e-5	0.4585	No statistically significant relationship.

The regression analyses indicate a robust positive relationship between the number of trips and gasoline consumption, thereby confirming our initial hypothesis. Additionally, the presence of CNG stations and the prevalence of dual-fuel vehicles significantly influence gasoline and CNG consumption patterns, as anticipated. However, several variables showed no statistically significant correlations, suggesting a need for further analysis or refinement of the model.

3.2. Data analysis and software utilization

The analysis for this study was performed using a combination of software tools tailored for various aspects of the research. Initially, descriptive data analysis was conducted using Microsoft Excel to calculate average growth rates for key variables, including gasoline production, gasoline consumption, and the prices of gasoline and CNG. The growth rates were computed using the following formula:

$$X_t = X_0(1 + g)^{t-0} \quad (1)$$

Where g represents the annual growth rate of the variable X_t .

For the quantitative and statistical analysis aimed at estimating the coefficients of the dynamic model, EViews was utilized to implement multivariate regression analysis, which facilitated a thorough examination of the relationships among the variables influencing gasoline consumption.

Moreover, dynamic systems analysis of gasoline consumption was performed using Stella software. This approach allowed us to develop causal loop diagrams and stock-flow diagrams, along with their corresponding formulations, to illustrate and analyze the feedback mechanisms within the gasoline consumption system.

Ultimately, the outputs generated by Stella were instrumental in conducting comprehensive research analyses, providing valuable insights into the system's dynamics and enabling a thorough understanding of the factors influencing gasoline consumption in Iran.

3.3. *Validation of the dynamic model*

The model was validated using complementary methods:

1. Comparison with historical data (2006-2021): We compared model outputs with actual consumption data from the National Iranian Oil Products Distribution Company (NIOPDC). The model demonstrated:

- ✓ Excellent predictive accuracy ($R^2 = 0.93$)
- ✓ Mean absolute error of 4.7%
- ✓ Root mean square error of 6.2%

Notably, the model successfully replicated the 15% reduction in consumption following the 2019 fuel rationing policy (Fig. 5a).

2. Sensitivity analysis: Parameter sensitivity was tested through Monte Carlo simulations ($\pm 20\%$ variation):

- ✓ Gasoline price elasticity showed the greatest impact ($\pm 18\%$ consumption change)
- ✓ CNG infrastructure expansion potential ($\pm 12\%$)
- ✓ Dual-fuel vehicle adoption rate ($\pm 15\%$)

All parameters were statistically significant ($p < 0.01$) using Sobol's sensitivity indices.

3. Cross-Validation: We employed k-fold cross-validation ($k=5$):

- ✓ Training period: 2006-2017 (80% of data)
- ✓ Testing period: 2018-2021 (20% of data)

Model performance remained consistent across all folds:

- ✓ MAE range: 4.2-5.1%
- ✓ RMSE range: 5.8-6.5%

In conclusion, these validation methods confirmed that the model effectively predicts fuel consumption dynamics, establishing it as a valuable tool for energy policy analysis in Iran.

4. Results

4.1. *Simulation outcomes of the dynamic model*

The final stock and flow model (see Figure 4) integrates the regression results, illustrating the interconnectedness of various factors influencing gasoline consumption. In this diagram,

thicker arrows indicate stronger and more direct relationships among the variables.

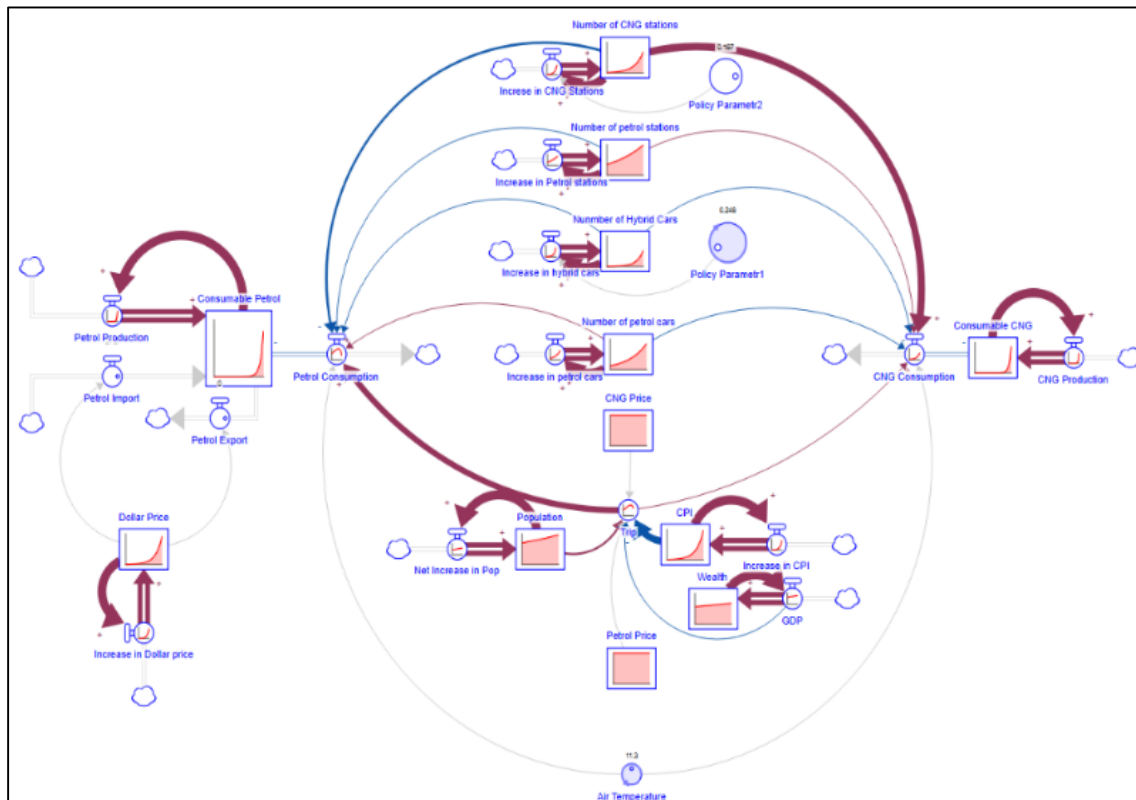


Figure 4. Stock and flow diagram of the simulated dynamic model for gasoline consumption

The analysis reveals a strong positive correlation between the number of trips and gasoline consumption. Other factors—such as population, GDP, CPI, gasoline and CNG prices, the number of CNG stations, and the prevalence of hybrid vehicles—primarily impact gasoline consumption through their influence on the number of trips. Notably, the policy interventions (designated as Policy Parameters 1 and 2) are designed to affect gasoline consumption indirectly by influencing the growth of hybrid vehicles and the establishment of CNG stations. While Figure 4 captures key dynamic relationships, Variables such as population death rate and foreign exchange trends were excluded due to their indirect temporal impact on gasoline consumption. These may be considered in future iterations for macroeconomic expansion.

4.2. Forecasting results

Following the initial design of the dynamic model, validation is essential for its practical application. To this end, gasoline consumption data from Iran (2006-2021), along with other relevant model variables, were integrated into the dynamic model. The simulated data were then compared against actual historical consumption data as presented in Table 7.

Table 7. Comparison of actual and simulated gasoline consumption (2006-2021)

Year	Actual Consumption (k liters)	Simulated consumption (k liters)
2006	73,660	48,800
2007	64,450	51,900
2008	66,931	55,000
2009	64,800	58,200
2010	61,267	61,300
2011	59,857	64,300
2012	63,493	67,400
2013	68,409	70,400
2014	69,591	73,300
2015	71,003	76,100
2016	74,741	78,700
2017	80,714	81,200
2018	89,115	83,500
2019	89,000	85,500
2020	75,000	87,100
2021	86,000	88,300

Table 8. Gasoline consumption forecast (2022-2031)

Year	Forecasted consumption (thousands of liters)
2022	89,000
2023	89,000
2024	88,100
2025	86,200
2026	83,100
2027	78,500
2028	71,900
2029	63,100
2030	51,400
2031	36,200

The model projects gasoline consumption to decrease to 36,200,000 liters by 2031 as shown in Table 8. In contrast, a simple extrapolation based on the average annual growth rate of 4.35% would suggest consumption could reach 131,666,000 liters. This predicted downward trend from 2023 to 2031 can be attributed to several factors, including significant inflation that reduces purchasing power, shifting priorities regarding travel expenditures, technological advancements that yield more fuel-efficient vehicles, and the growing prevalence of online shopping and remote work. The dynamic model's forecast suggests a more conservative outlook than the simple extrapolation, reflecting the model's incorporation of complex, non-linear interrelationships among the various influencing factors, which may result in more accurate predictions.

4.3. Sensitivity analysis

This section presents a sensitivity analysis of the dynamic model used to predict gasoline consumption in Iran. The base model incorporates coefficients of 0.17295 and 0.18702,

corresponding to the average annual growth rates of dual-fuel vehicles and CNG stations, respectively, from 2006 to 2020. Three scenarios were simulated to assess model sensitivity to variations in these parameters (see Table 9):

Scenario 1: Increased annual growth rate of dual-fuel vehicles from 0.17295 to 0.35.

Scenario 2: Increased annual growth rate of CNG stations from 0.18702 to 0.22.

Scenario 3: Simultaneous increase of both parameters (Scenario 1 and Scenario 2 combined)

Table 9. Gasoline consumption forecast (2022-2031) under different scenarios

Year	Forecasted consumption (thousands of liters)- base mode	Scenario 1	Scenario 2	Scenario 3
2022	89,000	88	87	86
2023	89,000	87	87	86
2024	88,100	86	86	84
2025	86,200	80	84	81
2026	83,100	76	80	77
2027	78,500	68	74	70
2028	71,900	58	67	62
2029	63,100	45	57	50
2030	51,400	42	44	35
2031	36,200	24	27	15

- Scenario 1 (Increased Dual-Fuel Vehicles): This scenario indicates a significant reduction in gasoline consumption by 2031, decreasing from 36,200,000 liters to 24,000,000 liters, underscoring the strong influence of dual-fuel vehicle adoption on gasoline demand. The effect becomes increasingly pronounced in the later years.
- Scenario 2 (Increased CNG Stations): This scenario reflects a less dramatic reduction in gasoline consumption, with projected consumption reaching 27,000,000 liters by 2031. The impact is notably less substantial during the earlier years of the forecast period.
- Scenario 3 (Combined Effect): This scenario demonstrates the most significant decrease in gasoline consumption, projecting a reduction to 15,000,000 liters by 2031. This highlights the synergistic effect of enhancing both dual-fuel vehicle and CNG station accessibility.

The sensitivity analysis indicates that policy initiatives targeting the promotion of dual-fuel vehicles and the expansion of CNG infrastructure could significantly reduce gasoline consumption in Iran. Among the scenarios, Scenario 3, which represents an integrated policy approach, proves to be the most effective. However, the reliability of the model's forecasts depends on the accuracy of the growth rate estimates and the consideration of other relevant factors. Figure 5 illustrates the comparison of predicted gasoline consumption outcomes across the different scenarios.

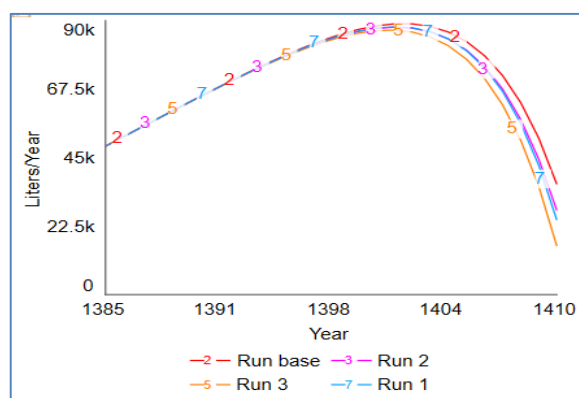


Figure 5. Comparison of predicted gasoline consumption under different scenarios

5. Discussion

This study aimed to explore the dynamics of gasoline consumption in Iran through a comprehensive dynamic model that incorporates various influencing factors, such as economic conditions, vehicle types, and policy interventions. The simulation results indicate a robust positive correlation between the number of trips and gasoline consumption, suggesting that travel behavior is a critical driver of fuel demand. This finding aligns with previous research indicating that increases in mobility are closely linked to rising fuel consumption.

The impact of policies aimed at promoting dual-fuel vehicles and expanding CNG stations was particularly noteworthy. This outcome aligns with findings from [Raei et al. \(2024\)](#), who evaluated the effects of energy policy reforms on fuel consumption and emissions in Iran, as well as [Maleki et al. \(2024\)](#), who highlighted the strategic role of transitioning toward clean energy in national policy frameworks.

The sensitivity analysis revealed that both interventions could significantly mitigate gasoline demand, with Scenario 3—combining increased adoption of dual-fuel vehicles and expansion of CNG infrastructure—demonstrating the most substantial reduction in projected consumption. These results underscore the effectiveness of integrated policy approaches. They also reflect a growing global consensus that multi-pronged strategies are essential for achieving meaningful energy transitions and reducing fuel dependency.

Furthermore, the forecasting results indicate a marked decline in gasoline consumption over the next decade, with predictions stabilizing at levels considerably lower than those extrapolated from historical growth rates. This divergence suggests the importance of accounting for structural changes within the economy, such as technological advancements and shifts in consumer behavior, which simple extrapolation methods may not capture. Key factors identified, including inflation, increased fuel efficiency, and trends toward online shopping and

remote work, highlight the need for policymakers to consider broader economic shifts when developing strategies to manage fuel consumption. Additionally, the proposed system dynamics model was benchmarked against reference frameworks such as the C-ROADS climate simulator and Ford's energy policy dynamics (Ford, 2020). Compared to these models, our framework offers greater granularity in fuel infrastructure and vehicle segmentation, making it better suited for national-level policy analysis.

6. Conclusion

In conclusion, this study provides valuable insights into the determinants of gasoline consumption in Iran, highlighting the roles of trip frequency and vehicle type in shaping fuel demand patterns. The dynamic model developed herein offers a nuanced understanding of how various factors interact within the fuel consumption system, providing a platform for informed decision-making.

The findings underscore the importance of implementing policies that do not merely aim to increase fuel availability but also encourage shifts toward more sustainable vehicle technologies. By promoting the adoption of dual-fuel vehicles and expanding CNG infrastructure, Iran can potentially reduce its reliance on gasoline, alleviate environmental pressures, and enhance energy security.

Future research should seek to refine the model further by incorporating additional variables, such as changes in consumer behavior in response to economic shocks, policies targeting public transportation, and the impact of renewable energy adoption. Additionally, longitudinal studies could provide deeper insights into how these factors evolve and their implications for Iran's long-term energy policy.

Disclosure statement

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

References

Abediasl, H., Ansari, A., Hosseini, V., Koch, C.R. and Shahbakhti, M., 2024. Real-time vehicular fuel consumption estimation using machine learning and on-board diagnostics data. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 238(12), pp.3779-3793. <https://doi.org/10.1177/09544070231185609>.

- Akbari, F., Mahpour, A. and Ahadi, M.R., 2020. Evaluation of energy consumption and CO₂ emission reduction policies for urban transport with system dynamics approach. *Environmental Modeling & Assessment*, 25(4), pp.505-520. <https://doi.org/10.1007/s10666-020-09695-w>.
- Al-Ghandoor, A., Jaber, J., Al-Hinti, I. and Abdallat, Y., 2013. Statistical assessment and analyses of the determinants of transportation sector gasoline demand in Jordan. *Transportation Research Part A: Policy and Practice*, 50, pp.129-138. <https://doi.org/10.1016/j.tra.2013.01.022>.
- Allen, T. and Arkolakis, C., 2022. The welfare effects of transportation infrastructure improvements. *The Review of Economic Studies*, 89(6), pp.2911-2957. <https://doi.org/10.1093/restud/rdac001>.
- An-loh, L., Botsas, E.N. and Monroe, S.A., 1985. State gasoline consumption in the USA: an econometric analysis. *Energy Economics*, 7(1), pp.29-36. [https://doi.org/10.1016/0140-9883\(85\)90036-2](https://doi.org/10.1016/0140-9883(85)90036-2).
- Ansarinasab, M. and Manzari Tavakoli, Z., 2020. Modeling Gasoline Consumption Behaviors in Iran Based on Long Memory and Regime Change. *Quarterly Energy Economics Review*, 16(64), pp.125-149. URL: <http://iiesj.ir/article-1-1145-en.html>. [in Persian].
- Ayyıldız, E. and Murat, M., 2024. A lasso regression-based forecasting model for daily gasoline consumption: Türkiye Case. *Turkish Journal of Engineering*, 8(1), pp.162-174. <https://doi.org/10.31127/tuje.1354501>.
- Bates, M. and Kim, S., 2024. Estimating the price elasticity of gasoline demand in correlated random coefficient models with endogeneity. *Journal of Applied Econometrics*, 39(4), pp.679-696. <https://doi.org/10.1002/jae.3042>.
- Bayat, N., Davoodi, M.M. and Rezaei, A., 2023. Forecasting Gasoline Consumption in Iran using Deep Learning Approaches. *Iranian Economic Review*, 27(2), pp.347-376. [10.22059/ier.2023.317681.1007087](https://doi.org/10.22059/ier.2023.317681.1007087).
- Ceylan, Z., Akbulut, D. and Baytürk, E., 2024. Forecasting gasoline consumption using machine learning algorithms during COVID-19 pandemic. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 46(1), pp.16623-16641. <https://doi.org/10.1080/15567036.2021.2024919>.
- Chang, C.C., 2016. Causal analysis of carbon emissions, deadweight tonnage of global shipping fleet, fuel oil consumption, and economic activities in marine transportation. *Energy Sources, Part B: Economics, Planning, and Policy*, 11(4), pp.303-308. <https://doi.org/10.1080/15567249.2011.607884>.
- Ford, A., 2018. System dynamics models of environment, energy, and climate change. In *Encyclopedia of complexity and systems science* (pp. 1-25). Springer, Berlin, Heidelberg.
- Ghoddusi, H., Morovati, M. and Rafizadeh, N., 2019. Foreign exchange shocks and gasoline consumption. *Energy Economics*, 84, p.104472. <https://doi.org/10.1016/j.eneco.2019.08.005>.
- Goetzke, F. and Vance, C., 2021. An increasing gasoline price elasticity in the United States?. *Energy economics*, 95, p.104982. <https://doi.org/10.1016/j.eneco.2020.104982>.
- Heidari, E., Bikdeli, S. and Daneshvar, M.R.M., 2023. A dynamic model for CO₂ emissions induced by urban transportation during 2005–2030, a case study of Mashhad, Iran. *Environment, Development and Sustainability*, 25(5), pp.4217-4236. <https://doi.org/10.1007/s10668-022-02240-7>.
- Iran Chamber Newsroom, 2024. Iran's average daily gasoline consumption reaches 113m liters. Available at: <https://en.otaghiranonline.ir/news/45254>.

- Jafari, H.H. and Baratimalayeri, A., 2008. The crisis of gasoline consumption in the Iran's transportation sector. *Energy Policy*, 36(7), pp.2536-2543. <https://doi.org/10.1016/j.enpol.2008.03.014>.
- Kilian, L. and Zhou, X., 2024. Heterogeneity in the pass-through from oil to gasoline prices: A new instrument for estimating the price elasticity of gasoline demand. *Journal of Public Economics*, 232, p.105099. <https://doi.org/10.1016/j.jpubeco.2024.105099>.
- Lee, C.C. and Olasehinde-Williams, G., 2021. Gasoline demand elasticities in the world's energy gluttons: a time-varying coefficient approach. *Environmental Science and Pollution Research*, 28(45), pp.64830-64847. <https://doi.org/10.1007/s11356-021-15615-6>.
- Maleki, A., Ashrafi, M.H. and Raei, H., 2024. Overview of energy policy in Iran: the proper path to clean energy. *Academia Green Energy*, 1(2). <https://doi.org/10.20935/AcadEnergy7316>.
- Mikayilov, J.I., Joutz, F.L. and Hasanov, F.J., 2020a. Gasoline demand in Saudi Arabia: are the price and income elasticities constant?. *Energy Sources, Part B: Economics, Planning, and Policy*, 15(4), pp.211-229. <https://doi.org/10.1080/15567249.2020.1775325>.
- Mikayilov, J.I., Mukhtarov, S. and Mammadov, J., 2020b. Gasoline demand elasticities at the backdrop of lower oil prices: Fuel-subsidizing country case. *Energies*, 13(24), p.6752. <https://doi.org/10.3390/en13246752>.
- Moshiri, S. and Aliyev, K., 2017. Rebound effect of efficiency improvement in passenger cars on gasoline consumption in Canada. *Ecological economics*, 131, pp.330-341. <https://doi.org/10.1016/j.ecolecon.2016.09.018>.
- Moshiri, S., 2020. Consumer responses to gasoline price and non-price policies. *Energy Policy*, 137, p.111078. <https://doi.org/10.1016/j.enpol.2019.111078>.
- Mosleh Shirazi, A.N. and Sotodeh, F., 2015. Simulating the role of subsidies reform in fuel consumption by system dynamics approach. *Journal of Applied Economics Studies in Iran*, 4(13), pp.107-125. URL:https://aes.basu.ac.ir/article_1036_en.html. [in Persian].
- Newman, P. and Kenworthy, J., 2021. Gasoline consumption and cities revisited: what have we learnt?. *Current Urban Studies*, 9(3), pp.532-553. <https://doi.org/10.4236/cus.2021.93032>.
- Nitoiu, C., Cofaru, C. & Popescu, M., 2025. Influence of road and traffic conditions on emissions and fuel consumption of light vehicles in a real urban driving cycle. *Environmental Science and Pollution Research* 32, pp. 15050–15065. <https://doi.org/10.1007/s11356-025-36573-3>.
- Norouzi, N., Majedi, S. and Abbasi, V., 2022. Dynamic modeling of the effect of Vehicle Hybridization policy on carbon emission and energy consumption. *Journal of Chemistry Letters*, 3(2), pp.99-107. <https://doi.org/10.22034/jchemlett.2022.352806.1078>.
- Pourmatin, M., Moeini-Aghaie, M., Hassannayebi, E. and Hewitt, E., 2024. Transition to Low-Carbon Vehicle Market: Characterization, System Dynamics Modeling, and Forecasting. *Energies*, 17(14), p.3525. <https://doi.org/10.3390/en17143525>.
- Raei, H., Maleki, A. and Farajzadeh, Z., 2024. Analysis of energy policy reform in Iran: Energy and emission intensity changes. *Economic Analysis and Policy*, 81, pp.1535-1557. <https://doi.org/10.1016/j.eap.2024.02.023>.

- Rogat, J. and Sterner, T., 1998. The determinants of gasoline demand in some Latin American countries. *International Journal of Global Energy Issues*, 11(1-4), pp.162-170. <https://doi.org/10.1504/IJGEI.1998.071441>.
- Romero, C.A., Correa, P., Ariza Echeverri, E.A. and Vergara, D., 2024. Strategies for reducing automobile fuel consumption. *Applied Sciences*, 14(2), p.910. <https://doi.org/10.3390/app14020910>.
- Roudbaraki, M., Valipour, M.S., Khorasani, A.F. and Salehi, G.R., 2025. Integrating Data Mining and System Dynamics to Model Energy Policy Development and Sustainability Assessment. *Petroleum Business Review (PBR)*, 9(1). <https://doi.org/10.22050/pbr.2025.475979.1348>.
- Salimi, M., Moradi, M.A. and Amidpour, M., 2022. Modeling and outlook analysis of gasoline supply and demand and sensitivity analysis of main economic and social drivers. *Energy*, 256, p.124686. <https://doi.org/10.1016/j.energy.2022.124686>.
- Samavi, M., Panahi, M., Abedi, Z. and Ahmadian, M., 2024. Assessing the Economic Impact of Using ITSs (Intelligent Transportation Systems) on Gasoline Consumption in Iran (Case Study of Karaj-Chalous Axis). *Road*, 32(120), pp.331-348. <https://doi.org/10.22034/road.2023.367900.2107>. [in Persian].
- Sapnken, E.F., Tamba, J.G., Essiane, S.N., Koffi, F.D. and Njomo, D., 2018. Modeling and forecasting gasoline consumption in Cameroon using linear regression models. *International Journal of Energy Economics and Policy*, 8(2), pp.111-120. URL: <https://www.econjournals.com/index.php/ijee/article/view/5985>.
- Saryazdi, A.H.G. and Tavangar, L., 2023. Dynamics of Gasoline Price Changes; The Effects of Pricing Policies in Iran. <https://doi.org/10.21203/rs.3.rs-3394892/v1>.
- Shamsapour, N., Hajinezhad, A. and Noorollahi, Y., 2021. Developing a system dynamics approach for CNG vehicles for low-carbon urban transport: a case study. *International journal of low-carbon technologies*, 16(2), pp.577-591. <https://doi.org/10.1093/ijlct/ctaa085>.
- Vafa-Arani, H., Jahani, S., Dashti, H., Heydari, J. and Moazen, S., 2014. A system dynamics modeling for urban air pollution: A case study of Tehran, Iran. *Transportation Research Part D: Transport and Environment*, 31, pp.21-36. <https://doi.org/10.1016/j.trd.2014.05.016>.
- Yang, Y., Gong, N., Xie, K. and Liu, Q., 2022. Predicting gasoline vehicle fuel consumption in energy and environmental impact based on machine learning and multidimensional big data. *Energies*, 15(5), p.1602. <https://doi.org/10.3390/en15051602>.
- Yu, L., Ma, Y. and Ma, M., 2021. An effective rolling decomposition-ensemble model for gasoline consumption forecasting. *Energy*, 222, p.119869. <https://doi.org/10.1016/j.energy.2021.119869>.
- Zareayan Mazrae Khosro, R. and Shakouri Ganjavi, H., 2016. System Analysis Gasoline Demand and Estimating the Price Elasticity in the Province of Tehran, *Iranian Energy Economics*, 5(18), pp. 61–98. <https://doi.org/10.22054/jiee.2016.7193>. [in Persian]



System Dynamics Modeling of Preventive Care Strategies for Addressing Obesity and Healthcare Expenditures in the United States

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ABSTRACT

This study examines the impact of preventive care strategies on obesity prevalence and associated healthcare expenditures in the United States using system dynamics modeling. Obesity is a multifaceted public health challenge involving interdependent behavioral, biological, economic, and systemic factors that interact nonlinearly and evolve, which are characteristics of a complex system. To better understand these dynamics, we developed causal loop diagrams (CLDs) based on a rapid literature review, which mapped the feedback structures among key variables, including dietary behavior, physical activity, healthcare access, and the progression of obesity-related illnesses. The resulting CLDs identify both reinforcing and balancing feedback loops that govern transitions across population health states (healthy, pre-obese, obese, and chronically ill), as well as resource allocation dynamics within the healthcare system. This study makes a unique contribution by developing a comprehensive conceptual model that maps preventive care strategies using system dynamics feedback structures. Unlike prior models that focus narrowly on either physiological or behavioral factors, our model integrates multi-level pathways – behavioral, clinical, and economic – highlighting leverage points for policy intervention. The model reveals leverage points where upstream interventions, such as improving dietary behavior or increasing access to primary care, may disrupt harmful cycles and reduce long-term healthcare costs. These findings offer policymakers a systems-oriented perspective on where and how to intervene to curb the obesity epidemic and its associated economic burden.

Keywords

System dynamics, Obesity, Healthcare cost, Health policy, Preventive care, Causal loop diagram.

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1. Introduction

Obesity is a major contributor to the exorbitant healthcare expenses in the United States. According to the Centers for Disease Control and Prevention (CDC), the healthcare system in the USA spends a staggering \$173 billion annually due to obesity-related issues (CDC, 2022). The burden of obesity on the healthcare system is escalating, and it becomes disproportionately high for the most obese portion of the U.S. population (Williams et al., 2015). Between 2000 and 2018, the prevalence of obesity among adults increased by nearly 10% (Hales, 2020). A comprehensive review of the literature on the causal effects of obesity on economic outcomes reveals that it escalates medical care expenses, diminishes the likelihood of finding employment, and reduces earnings and wages (Biener et al., 2018; Lee et al., 2017; Yusefzadeh et al., 2019). Some researchers suggest that the prevention of obesity could potentially result in substantial healthcare cost savings (Avenell et al., 2004; Cawley et al., 2015; Gortmaker et al., 2015).

In addition, obesity is associated with a range of health problems, including cardiovascular disease, hypertension, diabetes, and certain cancers (Aballay et al., 2013; Mozaffarian, 2016; Pi-Sunyer, 2009). Consequently, the progression of obesity into other diseases is associated with increased utilization of healthcare services, increased medication use, and higher rates of hospitalization and emergency room visits, all of which contribute to higher healthcare costs for obese individuals (Cecchini, 2018; Must et al., 1999; Suehs et al., 2017). One study found that healthcare costs for obese individuals were 42% higher than for individuals with a healthy weight (Finkelstein et al., 2009).

Obesity is a pressing public health predicament that has reached epidemic proportions globally (James et al., 2001). In the United States, the incidence of obesity has increased significantly across all demographic groups, primarily due to changes in dietary patterns and advancements in technology that have reduced physical exertion in labor-intensive occupations (Selvin et al., 2014). Overweight and obesity are linked to a heightened risk of multiple ailments and conditions (GBD 2015 Obesity Collaborators, 2017). Adults with obesity are more likely to develop heart disease, type 2 diabetes, and certain forms of cancer, which can result in elevated morbidity and mortality (Aballay et al., 2013). In general, obesity increases the likelihood of contracting other illnesses, thereby increasing healthcare utilization and expenses, while concurrently reducing life expectancy. Overall, obesity is a significant contributor to morbidity and mortality, as well as high medical expenses (Lehnert et al., 2013; Abdelaal et al., 2017). As depicted in Figure 1, healthcare costs in the US are also increasing rapidly, with a

significant portion of this growth attributable to obesity (Thorpe et al., 2004). Therefore, the problem that needs to be addressed is how to understand pathways for reducing the prevalence of obesity and associated healthcare costs.

To deepen the understanding of the economic ramifications of obesity, it is essential to consider the broader societal costs beyond direct healthcare expenses. These include indirect costs such as lost productivity, absenteeism, and presenteeism. Research indicates that obese individuals are more likely to miss work due to health-related issues. When they do work, their productivity can be lower due to obesity-related complications (Trogdon et al., 2008). It not only affects individuals but also places a strain on employers and the economy as a whole.

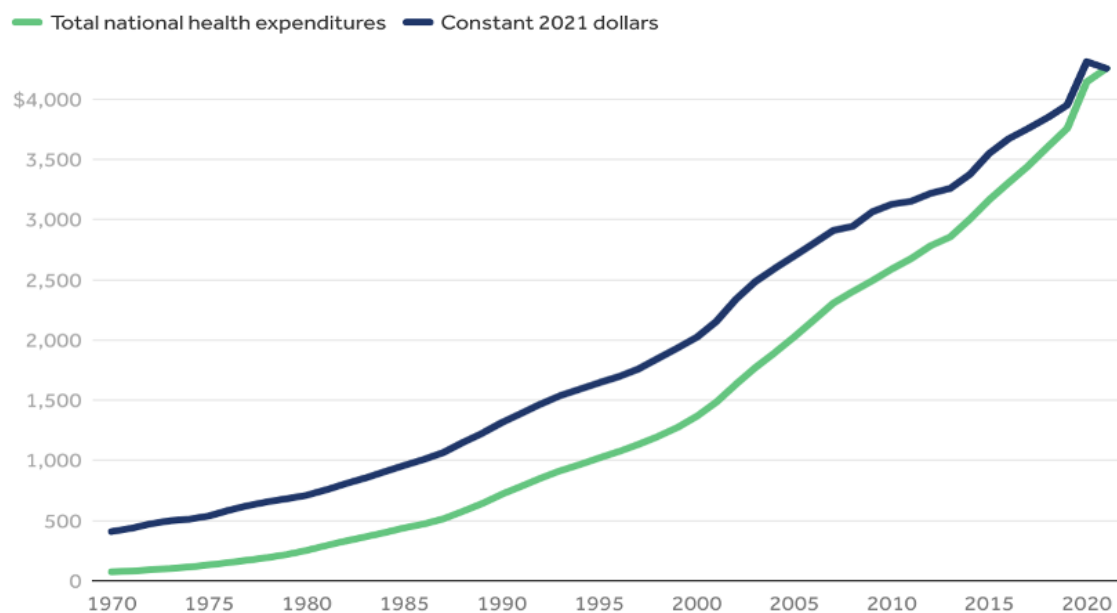


Figure 1. Annual national healthcare expenditures (in billion dollars) (Source: Kaiser Family Foundation)

Furthermore, the psychosocial impact of obesity cannot be overlooked. Obesity often leads to stigmatization and discrimination, which can exacerbate mental health issues such as depression and anxiety (Papadopoulos and Brennan, 2015). These mental health challenges, in turn, can further reduce the quality of life and increase healthcare costs due to the need for mental health services (Puhl and Heuer, 2009). Addressing obesity, therefore, requires a systems approach that encompasses physical, cognitive, and social health dimensions (Bagnall et al., 2019; Finegood, 2012; Lee et al., 2017).

Preventive measures play a critical role in addressing the obesity epidemic (World Health Organization, 2000). Public health interventions that promote healthy eating, physical activity, and behavioral changes are essential in preventing obesity from an early age. Policies that create healthier food environments, such as taxation on sugary beverages, subsidization of nutritious foods, and regulations on food marketing to children, have shown promise in reducing obesity

rates ([Mozaffarian, 2016](#)). Additionally, community-based programs that encourage physical activity through infrastructure improvements, such as the creation of parks and pedestrian-friendly urban designs, are crucial in fostering an environment conducive to maintaining a healthy weight.

The healthcare system itself must also adapt to better manage obesity. Integrating weight management programs into primary care, improving access to nutrition and physical activity counseling, and providing support for bariatric surgery where appropriate are important strategies. These healthcare interventions should be complemented by policies that address socioeconomic determinants of health, including education, income, and access to healthy foods and safe environments for physical activity ([Kumanyika, 2019](#)).

Moreover, the influence of digital technology and media on dietary habits and physical activity levels needs to be addressed. The rise of sedentary lifestyles due to increased screen time and the pervasive marketing of unhealthy foods through digital platforms significantly contributes to the obesity epidemic ([Golod, 2021](#)). Initiatives that promote digital wellness and responsible media consumption, alongside stricter regulations on the digital advertising of unhealthy foods, are necessary to combat this trend.

System dynamics is a methodology for understanding the behavior of complex systems over time ([Forrester, 1994](#); [Sterman, 1994](#)). By utilizing feedback loops, stock and flow diagrams, and differential equations, it models the dynamic interactions within a system. Developed by Jay W. Forrester in the 1950s, this approach is invaluable in public health for simulating the impact of various interventions and identifying leverage points within complex issues such as obesity ([Aguilar et al., 2023](#)). System dynamics offers a comprehensive understanding of the multifaceted factors contributing to obesity, facilitating the design of more effective and sustainable interventions ([Xue et al., 2018](#)).

A key tool in system dynamics is the causal loop diagram (CLD), which graphically represents the feedback loops and causal relationships within a system. CLDs use variables connected by arrows to indicate the direction and nature of influence (positive or negative). In addressing obesity, CLDs can map the interactions between dietary habits, physical activity, genetic predispositions, psychological factors, and socioeconomic conditions. By visualizing these relationships, CLDs help identify critical intervention points, allowing policymakers to disrupt negative feedback loops and promote positive change. This systematic approach is crucial for addressing the complexity of obesity, enabling more informed and effective decision-making.

To that end, the objective of this research is twofold. First, we develop a conceptual model to assess the impact of obesity and related complications on healthcare expenditures. Second, using CLDs, we examine how preventive care can help mitigate the costs associated with obesity. We contend that the findings of this research will provide valuable insights to healthcare policymakers in designing effective population-level interventions to address the rising prevalence of obesity. These insights could pave the way for comprehensive strategies that not only reduce obesity rates but also alleviate the associated economic burden on the healthcare system.

2. Methodology

We begin our study by conducting a rapid literature review on the topic of obesity and its impact on healthcare expenditure in the United States. For this literature search, we utilized three comprehensive databases: Scopus, Web of Science, and PubMed. These databases were chosen due to their extensive coverage of peer-reviewed journals and high-quality research articles relevant to our study. The literature review aimed to gather insights into the direct and indirect costs associated with obesity, the healthcare burden it imposes, and the effectiveness of various interventions aimed at mitigating these costs. This foundational step was crucial in understanding the current state of knowledge and identifying gaps that our research could address.

Based on the insights gleaned from this extensive literature review, we brainstormed the key variables that influence the relationship between obesity and healthcare expenditure. These variables were identified through a combination of empirical evidence from existing studies and theoretical considerations. Our brainstorming sessions included multidisciplinary perspectives to ensure a holistic understanding of the problem. By integrating these variables with our existing mental models, we developed CLDs, a widely used tool in system dynamics modeling. CLDs are instrumental in illustrating the feedback loops and complex interactions within a system, demonstrating how the escalating prevalence of obesity could potentially influence healthcare expenses over time.

The development of the CLDs was an iterative process that involved multiple refinements to accurately capture the dynamics of obesity and healthcare costs. Each iteration incorporated feedback from domain experts and refinements based on the latest empirical data. This rigorous process ensured that our final model was robust and reflective of real-world complexities. The resulting causal loop diagrams not only highlight the direct pathways through which obesity impacts healthcare costs but also reveal the underlying feedback mechanisms that sustain or

exacerbate this issue. The research framework for our study, which outlines these processes and connections, is depicted in Figure 2 below. This framework serves as the blueprint for our analysis, guiding our exploration of potential interventions to reduce obesity-related healthcare expenditures.

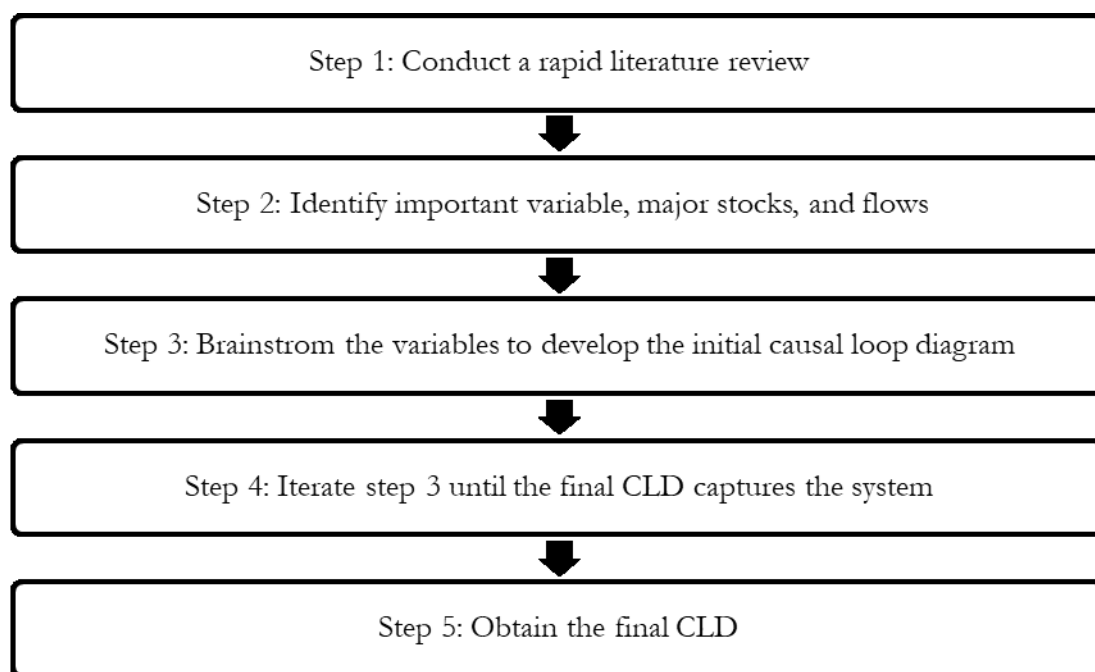


Figure 2. The research framework used in this study

3. Literature review

Numerous studies have established a link between obesity and the imbalance between energy intake and energy expenditure. Obesity occurs when individuals consistently consume more energy than they expend, leading to the accumulation of excess body fat (Abdel-Hamid, 2002; Abidin et al., 2014). Factors contributing to high energy intake include unhealthy eating behaviors such as high sugar consumption, frequent intake of fast foods, and continuous snacking (Mattes, 2014). Conversely, insufficient physical activity, whether through exercise or physical labor, prevents adequate energy expenditure, resulting in an energy imbalance (Fallah-Fini et al., 2014; Roberts et al., 2019). This imbalance increases average weight and consequently raises the body mass index (BMI), a key indicator of obesity. BMI is calculated by dividing a person's weight in kilograms by the square of their height in meters (Cole et al., 1995). According to the CDC, a BMI value of 30 or higher indicates obesity.

The progression from pre-obesity (BMI 25-29.9) to obesity underscores the dynamic nature of this condition. As the number of individuals with pre-obese BMI increases, a portion of this

population transitions to obesity, particularly if they do not receive proper treatment (Waterlander et al., 2021). This transition is often accompanied by the onset of comorbidities such as heart disease, high blood pressure, and diabetes, which further burden the healthcare system economically (Brittin et al., 2015). Consequently, addressing obesity is not only a matter of managing weight but also preventing associated health conditions that contribute to escalating healthcare costs.

Recent reviews have highlighted the effectiveness of system dynamics modeling in understanding and addressing chronic diseases, including obesity (Darabi and Hosseinichimeh, 2020; Davahli et al., 2020; Morshed et al., 2019). These studies have explored various strategies for reducing obesity, such as preventive care (Chen et al., 2018), improving access to healthy foods (Chiu et al., 2023), and increasing the prices of unhealthy foods (Guariguata et al., 2022). Community-wide prevention programs have also been examined for their potential to reduce obesity rates (Allender et al., 2015; Crielaard et al., 2020). Additionally, researchers have investigated the economic impact of obesity on healthcare costs, highlighting the significant financial strain it poses (Karanfil et al., 2011).

Preventive care is often posited as a solution to mitigate obesity-related healthcare costs (Homer et al., 2004; Homer et al., 2006; Zare Mehrjerdi, 2012; Jalali et al., 2014; Zainal Abidin et al., 2014). However, some researchers argue that preventive measures alone may not suffice in combating obesity effectively (van Baal et al., 2008). Implementing upstream measures and preventive care requires substantial government funding for pre-obesity interventions. While this could potentially reduce the prevalence of obesity and related healthcare expenditures, it necessitates a reallocation of resources that might be challenging to achieve (Zhao et al., 2008; Thompson and Wolf, 2001).

Overall, the literature underscores the complexity of obesity as a public health issue. It highlights the need for a multifaceted approach that includes preventive care, policy changes, and community interventions to address both the direct and indirect costs associated with obesity. Understanding these dynamics is crucial for developing effective strategies to reduce the prevalence of obesity and alleviate the economic burden on the healthcare system. To that end, this research applies a systems approach – system dynamics – to model the complexity of obesity.

4. System dynamics model

The final system dynamics model, prepared using Vensim PLE (shown in Figure 3), considers six major stocks: average weight, healthy population, pre-obese population, obese population,

population with obesity-related illnesses, and healthcare budget. In our CLD, we identify six balancing loops and six reinforcing loops. The first three balancing loops illustrate how initiatives such as improving physical activity and dietary behaviors can reduce the increase in average weight and prevent people from moving from a healthy state to a pre-obese state. The next three balancing loops demonstrate how allocating appropriate medical resources for treatment can prevent the progression of illness from one stage to a more critical stage. However, as the population moves downstream, the costs and utilization related to treating people with obesity and related illnesses increase.

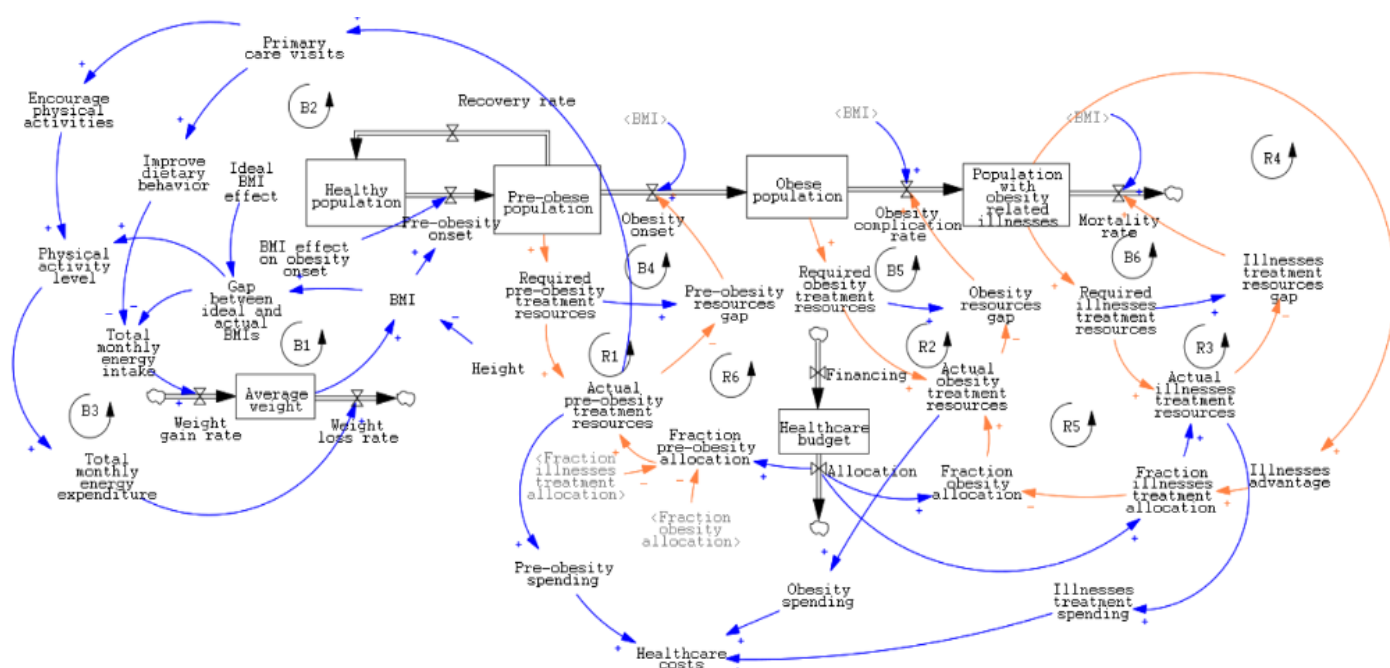


Figure 3. Overall causal loop diagram for preventive care for obesity

As more people become obese and their illness progresses to other types of chronic diseases, the costs and utilization associated with their treatments also increase. For example, as seen in the analysis of reinforcing loop 6, the population with obesity-related illnesses will have a higher priority for treatment, reducing the resources available for the healthy, pre-obese, and obese populations. This situation reinforces obesity rates and their associated illnesses, constantly demanding more resources for treatment and leaving the healthy population and those in the early stages of obesity unattended. The feedback loops are discussed below. Note that the labels B1–B6 and R1–R6 are assigned solely for reference and do not imply any ordering or prioritization of the feedback loops. An overview of the key variables employed in the feedback loops, along with their supporting references from the literature, is presented in Table 1.

Table 1. Mapping of feedback loops to supporting literature

Loop ID	Loop name	Key variables identified	Supporting references
B1	Obesity generation loop	BMI, energy intake, average weight	Abdel-Hamid (2002); Mattes (2014); Roberts et al. (2019)
B2	Prevention via dietary behavior loop	Pre-obese population, primary care visits, dietary behavior, energy intake, BMI	Abidin et al. (2014); CDC (2021); Chen et al. (2018)
B3	Prevention via physical activity loop	Primary care visits, physical activity level, energy expenditure, weight loss rate, BMI	Mozaffarian et al. (2012); Park et al. (2017); Lee et al. (2017)
B4	Pre-obese resource gap loop	Pre-obese population, required resources, actual allocation, resource gap, pre-obesity onset	Suehs et al. (2017); Zare Mehrjerdi (2012); Cecchini (2018)
B5	Obese resource gap loop	Obese population, required and allocated medical resources, resource gap, obesity complication rate	Finkelstein et al. (2009); Cecchini (2018); Fallah-Fini et al. (2014)
B6	Illness resource gap loop	Population with obesity-related illnesses, medical treatment resources, mortality rate	Abdelaal et al. (2017); Mozaffarian (2016); Suehs et al. (2017)
R1	Pre-obesity reinforcement loop	Pre-obese population, resource demand, allocation gap, obesity onset	Abidin et al. (2014); Jalali et al. (2014); Zainal Abidin et al. (2014)
R2	Obesity treatment loop	Obese population, healthcare visits, medication needs, resource allocation gap, obesity complications	Pi-Sunyer (2009); Cecchini (2018); CDC (2022)
R3	Chronic illness care demand loop	Chronic diseases (diabetes, CVD, cancer), hospitalization, medication use, mortality, healthcare costs	Aballay et al. (2013); Must et al. (1999); GBD 2015 Obesity Collaborators (2017)
R4	Illness treatment prioritization loop	Resource prioritization, actual resource allocation, mortality rate	Abdelaal et al. (2017); Cecchini (2018)
R5	Obesity resource reallocation loop	Healthcare budget constraints, allocation shift from obesity to illness treatment, obesity complication rate	Cawley et al. (2015); Zare Mehrjerdi (2012); Zhao et al. (2008)
R6	Pre-obesity resource allocation loop	Allocation shift from pre-obesity to illness care, guidance gap, pre-obesity onset	Park et al. (2017); Kumanyika (2019); Penn Medicine (2014)

4.1. Obesity generation loop – B1

A high BMI means an increased gap between the ideal BMI (according to a person's height) and their actual BMI. The higher gap should reduce the total monthly energy intake by that individual. As the monthly energy intake decreases, it reduces the average weight, and thus the BMI should decrease, completing a balancing feedback loop (Figure 4).

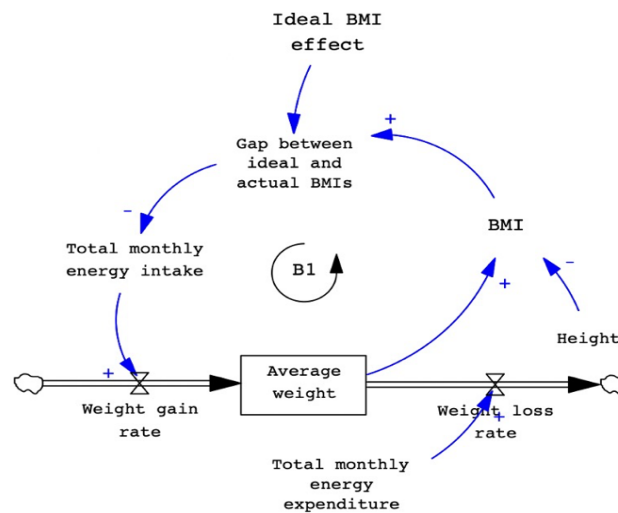


Figure 4. Obesity generation loop (B1)

4.2. Prevention via dietary behavior loop – B2

As the pre-obese population increases, it also increases the required amount of resources (such as treatment, medication, and equipment) for treating that population. It requires a higher actual allocation of pre-obese treatment resources. A higher allocation for such resources will enable a greater number of primary care visits for those individuals. Based on the guidance of primary care physicians (PCPs), the dietary behavior of that population would improve, resulting in a reduction of their monthly energy intake. As the monthly energy intake reduces, it decreases the average weight, and thus the BMI should decrease. A reduced BMI would further delay the onset of pre-obesity and eventually decrease the number of pre-obese individuals who complete a balancing feedback loop for prevention through dietary behavior control (Figure 5).

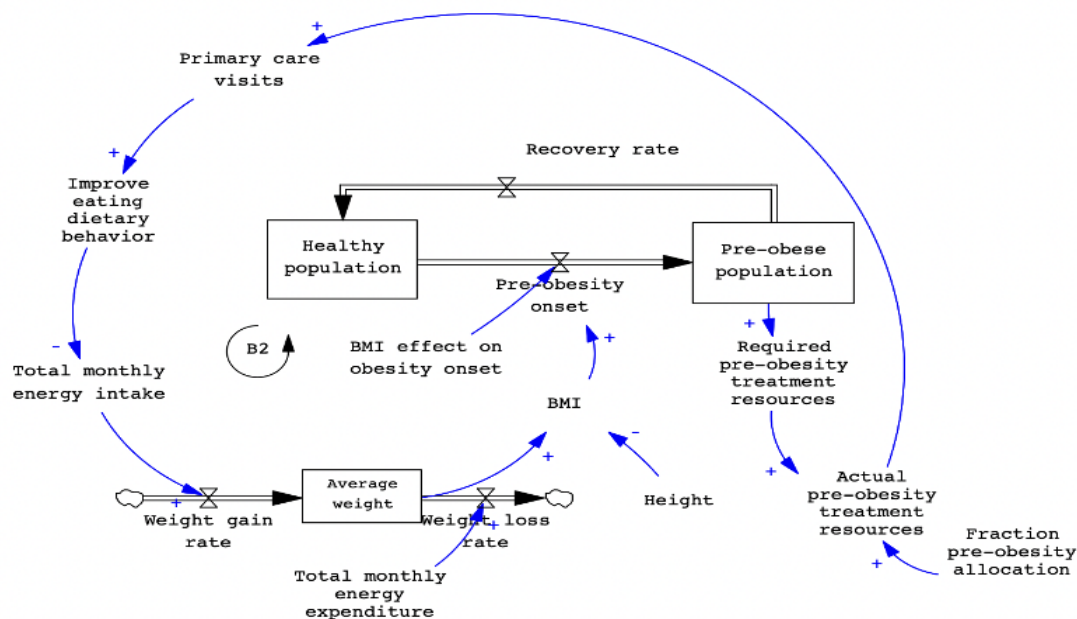


Figure 5. Prevention via dietary behavior loop (B2)

4.3. Prevention via physical activity loop – B3

A similar model behavior can be observed for prevention via physical activity measures, as shown in Figure 6. Increasing the population's access to primary care would likely lead to higher levels of physical activity. Meaning that their total monthly energy expenditure will go down, increasing the weight loss rate. It would reduce the average weight, consequently reducing the BMI, and ultimately decrease the number of individuals in the pre-obese population.

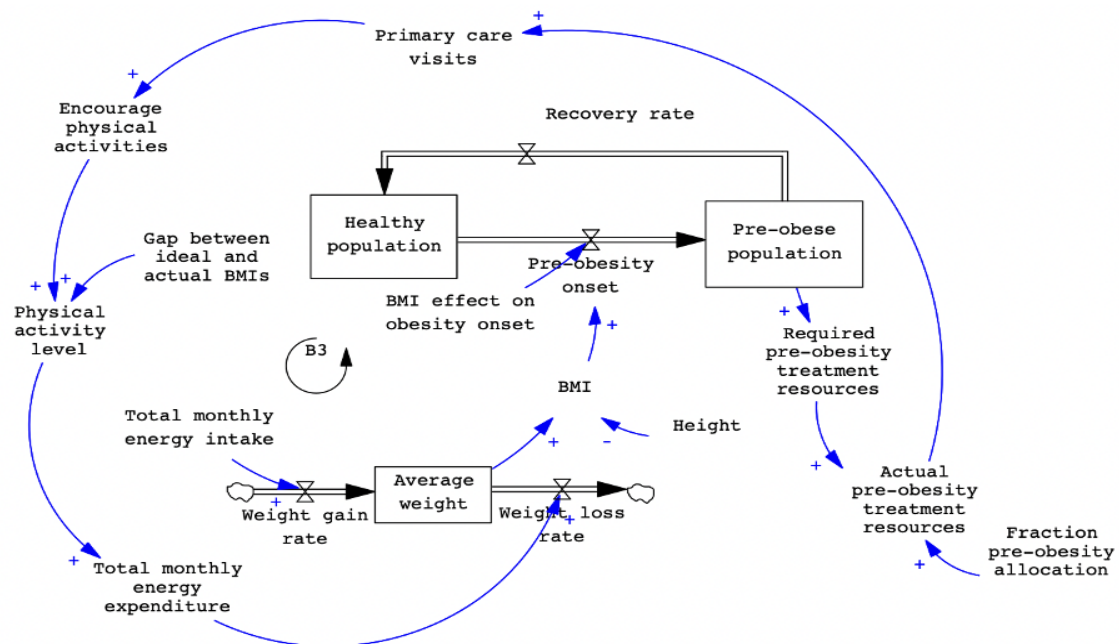


Figure 6. Prevention via physical activity loop (B3)

4.4. Required resources balancing loops – B4, B5, and B6

These three balancing loops explain how the pre-obese population, the obese population, and the population with obesity-related illnesses are influenced by the required resources for their corresponding treatment. For example, in the case of the B4 loop, an increased pre-obese population will require a higher amount of resources for treating that population. It would exacerbate the pre-obesity resources gap, which is the difference between the actual resources available and the required resources. A higher resource gap would increase the onset of pre-obesity, thereby reducing the pre-obesity population. The same behavior is also observed for the other two stock variables, as shown in Figure 7.

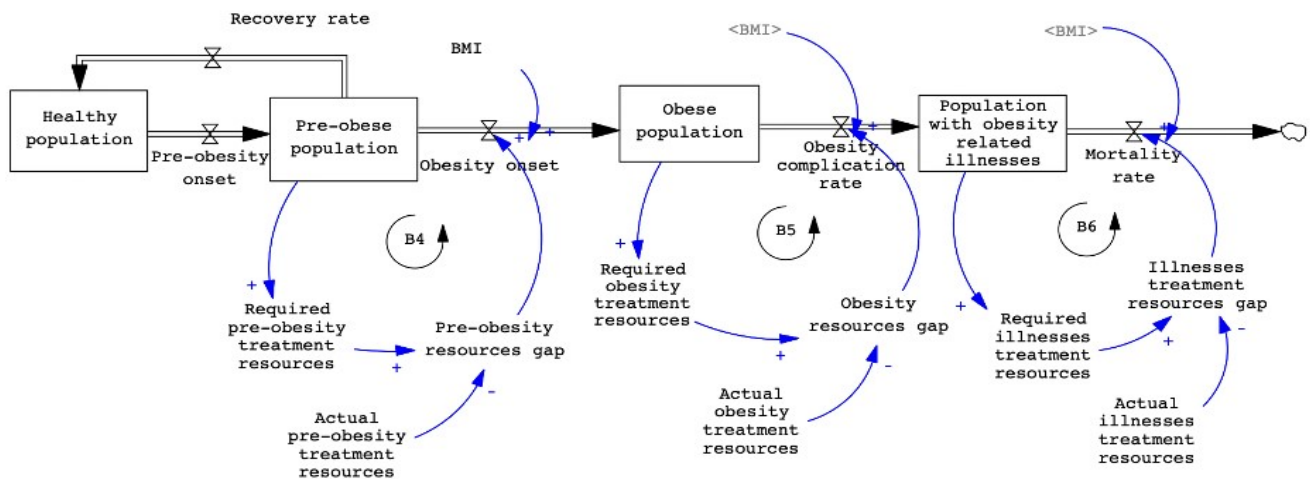


Figure 7. Required resources balancing loops (B4, B5, and B6)

4.5. Reinforcing loops – R1, R2, and R3

The population that moves from a healthy state to a state of pre-obesity begins to demand more resources, such as primary care visits and nutrition counseling, to prevent further weight gain and reduce the risk of developing obesity-related health issues. Based on the population suffering from pre-obesity, the resources required will increase; however, the fraction of the healthcare budget allocated for treating people in this stage may not be sufficient, creating a gap between the actual and required resources. A gap in resources can increase the onset of obesity, with more people reaching the obesity state (as depicted in Figure 8).

The same trend is observed in reinforcing loop 2, where populations that had reached a state of obesity may require more frequent visits to healthcare providers and hospitals for various health issues such as joint pain, sleep apnea, and respiratory problems. In addition, obese individuals may require medications for various obesity-related health issues, such as high blood pressure, high cholesterol, and type 2 diabetes. The gap between the medical services needed and the ones allocated by the healthcare budget can start increasing the obesity complication rate, as people do not receive treatment for their obesity condition. All these services increase healthcare utilization and can lead to higher costs for medical services and procedures.

For reinforcing loop 3, according to the CDC (2022), obesity is associated as a risk factor for several chronic health conditions, such as type 2 diabetes, heart disease, stroke, and certain types of cancer. These conditions require ongoing medical care, including drugs and hospitalizations, increasing the demand for medical resources for treating people with obesity-related illnesses. Once again, if the healthcare budget is not capable of allocating enough

resources to cover the medical treatments of people with chronic diseases, the mortality rate among the population can start increasing significantly.

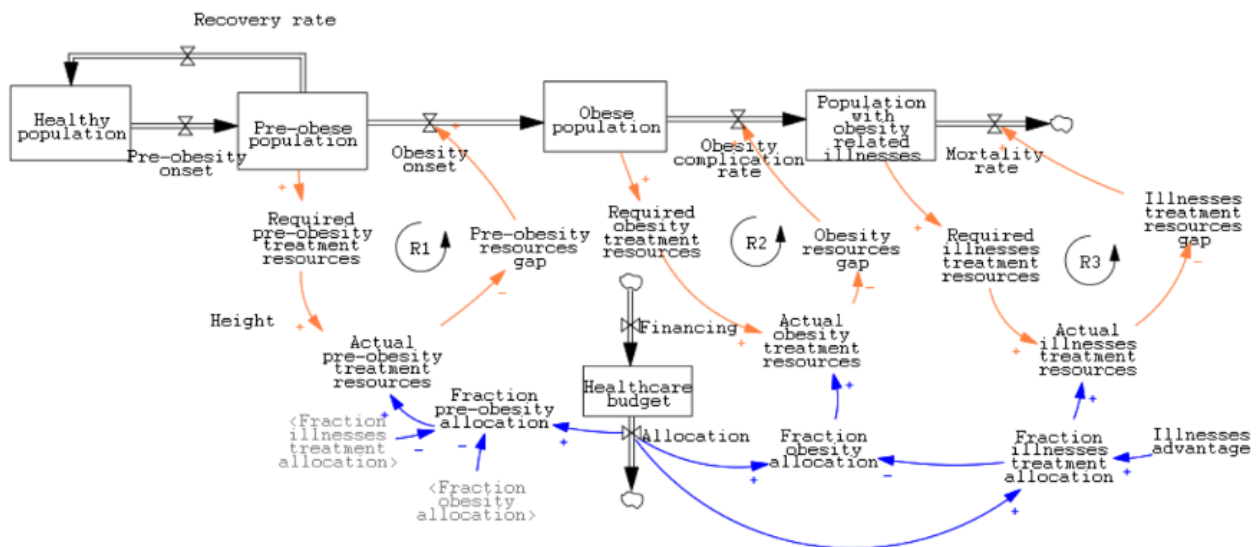


Figure 8. Reinforcing loops (R1, R2, and R3)

4.6. Reinforcing loops – R4, R5, and R6

The population with obesity related illnesses or the population suffering from chronic diseases has a high risk of mortality, which increases the advantage they have for accessing medical treatments, as the allocation of resources will be higher compared to this advantage. An increase in the actual resources for treating the population with obesity-related illnesses will reduce the gap and will reduce the level of mortality (Reinforcing loop 4, shown in Figure 9).

The advantage of the population with obesity-related illnesses has also affected the fraction of resources being allocated for treating the population with obesity. The fraction of obesity allocation is reduced by the fraction of resources earmarked for illness treatment, considering that the healthcare budget is limited. This decrease in the fraction of obesity allocation increases the gap in treating populations with obesity, which in turn increases the obesity complication rate (Reinforcing loop 5, shown in Figure 9). The same trend is observed for reinforcing loop 6, where the two fractions affect the pre-obesity allocation fraction by reducing it and increasing the demand for medical guidance and treatments among the population suffering from pre-obesity, thereby reinforcing the rate of obesity onset.

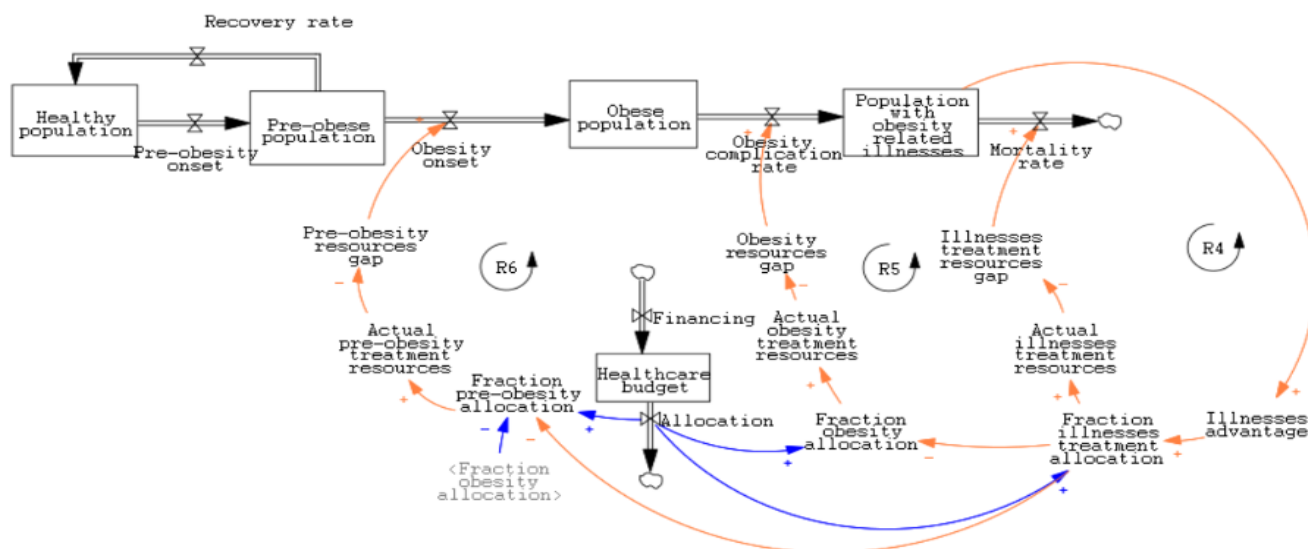


Figure 9. Reinforcing loops (R4, R5, and R6)

5. Policy implications

In terms of policy implications, our conceptual system dynamics model suggests that addressing the healthcare costs associated with obesity in the United States requires a shift towards preventive measures aimed at reducing the prevalence and incidence of obesity and its associated risk factors. Currently, the focus largely remains on managing chronic diseases after they have developed, rather than preventing their onset. This reactive approach results in healthy individuals transitioning to states of obesity or obesity-related illnesses at an alarming rate, underscoring the need for upstream interventions.

The CDC advocates for a multifaceted approach to addressing this issue, emphasizing the importance of creating healthier communities where individuals can make informed decisions about their health. This approach encompasses epidemiological surveillance to track trends and inform action, environmental interventions to promote healthy behaviors, improvements in healthcare systems to facilitate early prevention and management of chronic diseases, and fostering links between communities and clinical settings to support individuals in managing their health conditions.

To promote healthier choices and behaviors among the population, it is imperative to enhance access to primary care services and preventive interventions. Primary care physicians play a pivotal role in guiding individuals toward healthier lifestyles through dietary improvements, increased physical activity, and disease management support (Penn Medicine, 2014).

Furthermore, enhancing the delivery of primary preventive medical services is crucial to laying the foundation for population-wide health improvements.

Community-level initiatives aimed at improving access to healthy foods and discouraging the consumption of unhealthy options, through measures such as taxation, can have a significant impact on dietary habits. Similarly, promoting active mobility and enhancing access to recreational and fitness facilities can encourage physical activity and combat sedentary lifestyles (Park et al., 2017).

Implementing these solutions has the potential to reduce the prevalence of obesity and associated complications, thereby lowering the demand for healthcare resources dedicated to treating these conditions. By reallocating resources towards preventive measures and primary care services, we can enhance population health outcomes and alleviate the strain on the healthcare system. However, it is essential to recognize that the outcomes of these interventions may take time to materialize, necessitating sustained efforts and investments. Additionally, systemic barriers such as the lack of universal health insurance and profit-driven healthcare systems may pose challenges to the widespread adoption of preventive care approaches, necessitating policy reforms and stakeholder engagement to overcome resistance and drive meaningful change.

6. Conclusion and future work

In conclusion, addressing the healthcare costs associated with obesity in the United States necessitates an upstream approach focused on prevention. By promoting measures that encourage healthy lifestyles, fostering community commitment to making healthy choices, and enhancing access to primary care services, we can effectively reduce the onset of obesity and associated illnesses. This proactive approach not only optimizes the utilization of healthcare resources but also fosters a healthier population overall. Through these efforts, the U.S. can exert greater control over the progression of obesity, ultimately leading to a reduction in the number of individuals suffering from obesity-related ailments and an improvement in overall quality of life.

While our conceptual system dynamics model provides valuable insights based on existing literature, future research endeavors could further enhance its efficacy and impact. Integrating data from additional sources, such as expert opinions obtained through interviews and focus group discussions, as well as input from stakeholders like physicians and healthcare organizations, would strengthen the robustness of the model. By incorporating diverse

perspectives and real-world insights, we can refine our understanding of the complex dynamics underlying obesity and healthcare expenditures.

Moreover, there is potential for developing a quantitative simulation model to complement our conceptual framework. Such a model could be validated using comprehensive data on obesity rates and associated costs sourced from reliable databases like the CDC and the Kaiser Family Foundation. However, the accuracy and reliability of the model's predictions will hinge on the quality of the input data. Once established, this simulation model could serve as a powerful tool for quantitatively assessing the cost-effectiveness of various preventive care initiatives aimed at reducing obesity prevalence and mitigating long-term healthcare expenditures. Through continued interdisciplinary collaboration and methodological refinement, we can advance our capacity to address the complex challenges posed by obesity and work towards building a healthier future for all.

Disclosure statement

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

References

- Aballay, L.R., Eynard, A.R., Díaz, M.D.P., Navarro, A. and Muñoz, S.E., 2013. Overweight and obesity: a review of their relationship to metabolic syndrome, cardiovascular disease, and cancer in South America. *Nutrition reviews*, 71(3), pp.168-179. doi.org/10.1111/j.1753-4887.2012.00533.x.
- Abdel-Hamid, T.K., 2002. Modeling the dynamics of human energy regulation and its implications for obesity treatment. *System Dynamics Review: The Journal of the System Dynamics Society*, 18(4), pp.431-471. https://doi.org/10.1002/sdr.240
- Abdelaal, M., le Roux, C.W. and Docherty, N.G., 2017. Morbidity and mortality associated with obesity. *Annals of translational medicine*, 5(7), p.161. https://doi.org/10.21037/atm.2017.03.107.
- Abidin, N.Z., Zulkepli, J.H. and Zaibidi, N.Z., 2014, September. The effect of food portion sizes on the obesity prevention using system dynamics modelling. In *AIP Conference Proceedings*, 1613 (1), pp.436-443. American Institute of Physics. https://doi.org/10.1063/1.4894367.
- Aguiar, A., Gebremariam, M.K., Romanenko, E., Önal, F., Kopainsky, B., Savona, N., Brown, A., Allender, S. and Lien, N., 2023. System dynamics simulation models on overweight and obesity in children and adolescents: A systematic review. *Obesity Reviews*, 24, p.e13632. https://doi.org/10.1111/obr.13632.
- Allender, S., Owen, B., Kuhlberg, J., Lowe, J., Nagorcka-Smith, P., Whelan, J. and Bell, C., 2015. A community based systems diagram of obesity causes. *PloS one*, 10(7), p.e0129683. https://doi.org/10.1371/journal.pone.0129683
- Avenell, A., Broom, J., Brown, T.J., Poobalan, A., Aucott, L., Stearns, S.C., Smith, W.C.S., Jung, R.T., Campbell, M.K. and Grant, A.M., 2004. Systematic review of the long-term effects and economic

consequences of treatments for obesity and implications for health improvement. *Health technology assessment*, 8(21). <https://www.journalslibrary.nihr.ac.uk/#/>

Bagnall, A.M., Radley, D., Jones, R., Gately, P., Nobles, J., Van Dijk, M., Blackshaw, J., Montel, S. and Sahota, P., 2019. Whole systems approaches to obesity and other complex public health challenges: a systematic review. *BMC public health*, 19(1), pp.1-14. <https://doi.org/10.1186/s12889-018-6274-z>

Biener, A., Cawley, J. and Meyerhoefer, C., 2018. The impact of obesity on medical care costs and labor market outcomes in the US. *Clinical chemistry*, 64(1), pp.108-117. doi.org/10.1373/clinchem.2017.272450

Brittin, J., Araz, O.M., Nam, Y. and Huang, T.K., 2015. A system dynamics model to simulate sustainable interventions on chronic disease outcomes in an urban community. *Journal of Simulation*, 9(2), pp.140-155. <https://doi.org/10.1057/jos.2014.16>

Cawley, J., Meyerhoefer, C., Biener, A., Hammer, M. and Wintfeld, N., 2015. Savings in medical expenditures associated with reductions in body mass index among US adults with obesity, by diabetes status. *Pharmacoeconomics*, 33(7), pp.707-722. <https://doi.org/10.1007/s40273-014-0230-2>

CDC., 2022. Health and Economic Costs of Chronic Diseases. Retrieved from <https://www.cdc.gov/chronicdisease/about/costs/index.htm>

Cecchini, M., 2018. Use of healthcare services and expenditure in the US in 2025: The effect of obesity and morbid obesity. *PLoS One*, 13(11), p.e0206703. <https://doi.org/10.1371/journal.pone.0206703>

Chen, H.J., Xue, H., Liu, S., Huang, T.T., Wang, Y.C. and Wang, Y., 2018. Obesity trend in the United States and economic intervention options to change it: a simulation study linking ecological epidemiology and system dynamics modeling. *Public health*, 161, pp.20-28. <https://doi.org/10.1016/j.puhe.2018.01.013>

Chiu, S.K., Freebairn, L., Baur, L.A., Kreuger, L.K., Skinner, A. and Occhipinti, J.A., 2023. Modeling distribution parameters in system dynamics: an application in childhood obesity. *System Dynamics Review*, 39(2), pp.103-124. <https://doi.org/10.1002/sdr.1730>

Crielaard, L., Dutta, P., Quax, R., Nicolaou, M., Merabet, N., Stronks, K. and Sloot, P.M., 2020. Social norms and obesity prevalence: from cohort to system dynamics models. *Obesity Reviews*, 21(9), p.e13044. <https://doi.org/10.1111/obr.13044>

Cole, T.J., Freeman, J.V. and Preece, M.A., 1995. Body mass index reference curves for the UK, 1990. *Archives of disease in childhood*, 73(1), pp.25-29. <https://doi.org/10.1136/adc.73.1.25>

Darabi, N. and Hosseinichimeh, N., 2020. System dynamics modeling in health and medicine: a systematic literature review. *System Dynamics Review*, 36(1), pp.29-73. <https://doi.org/10.1002/sdr.1646>

Davahli, M.R., Karwowski, W. and Taiar, R., 2020. A system dynamics simulation applied to healthcare: A systematic review. *International journal of environmental research and public health*, 17(16), p.5741. <https://doi.org/10.3390/ijerph17165741>

Fallah-Fini, S., Rahmandad, H., Huang, T.T.K., Bures, R.M. and Glass, T.A., 2014. Modeling US adult obesity trends: a system dynamics model for estimating energy imbalance gap. *American journal of public health*, 104(7), pp.1230-1239. <https://doi.org/10.2105/AJPH.2014.301882>

- Finegood, D.T., 2012. The importance of systems thinking to address obesity. *Obesity treatment and prevention: New directions*, 73, pp.123-37. Karger Publishers.
- Finkelstein, E.A., Trogdon, J.G., Cohen, J.W. and Dietz, W., 2009. Annual Medical Spending Attributable To Obesity: Payer-And Service-Specific Estimates: Amid calls for health reform, real cost savings are more likely to be achieved through reducing obesity and related risk factors. *Health affairs*, 28(Suppl1), pp.w822-w831. <https://doi.org/10.1377/hlthaff.28.5.w822>.
- Forrester, J.W., 1994. System dynamics, systems thinking, and soft OR. *System dynamics review*, 10(2-3), pp.245-256. <https://doi.org/10.1002/sdr.4260100211>
- GBD 2015 Obesity Collaborators, 2017. Health effects of overweight and obesity in 195 countries over 25 years. *New England journal of medicine*, 377(1), pp.13-27. <https://doi.org/10.1056/NEJMoa1614362>.
- Golod, H., 2021. *Relationship between Social Media Screen Time, Sedentariness, and BMI among Young Adults* (Doctoral dissertation, Walden University).
- Gortmaker, S.L., Wang, Y.C., Long, M.W., Giles, C.M., Ward, Z.J., Barrett, J.L., Kenney, E.L., Sonneville, K.R., Afzal, A.S., Resch, S.C. and Cradock, A.L., 2015. Three interventions that reduce childhood obesity are projected to save more than they cost to implement. *Health Affairs*, 34(11), pp.1932-1939. <https://doi.org/10.1377/hlthaff.2015.0631>.
- Guariguata, L., Garcia, L., Sobers, N., Ferguson, T.S., Woodcock, J., Samuels, T.A., Guell, C. and Unwin, N., 2022. Exploring ways to respond to rising obesity and diabetes in the Caribbean using a system dynamics model. *PLOS Global Public Health*, 2(5), p.e0000436. <https://doi.org/10.1371/journal.pgph.0000436>.
- Hales, C.M., 2020. *Prevalence of Obesity and Severe Obesity Among Adults*. US Department of Health and Human Services, Centers for Disease Control and Prevention, National Center for Health Statistics.
- Homer, J., Milstein, B., Dietz, W., Buchner, D. and Majestic, E., 2006, July. Obesity population dynamics: exploring historical growth and plausible futures in the US. In *24th International System Dynamics Conference*. System Dynamics Society Albany, NY.
- Homer, J., Hirsch, G., Minniti, M. and Pierson, M., 2004. Models for collaboration: how system dynamics helped a community organize cost-effective care for chronic illness. *System Dynamics Review: The Journal of the System Dynamics Society*, 20(3), pp.199-222. <https://doi.org/10.1002/sdr.295>.
- Jalali, M., Rahmandad, H., Bullock, S. and Ammerman, A., 2014, July. Dynamics of obesity interventions inside organizations. In *The 32nd International Conference of the System Dynamics Society*. System Dynamics Society.
- James, P.T., Leach, R., Kalamara, E. and Shayeghi, M., 2001. The worldwide obesity epidemic. *Obesity research*, 9(S11), pp.228S-233S. <https://doi.org/10.1038/oby.2001.123>.
- Karanfil, O., Moore, T., Finley, P., Brown, T., Zagonel, A. and Glass, R., 2011. A multi-scale paradigm to design policy options for obesity prevention: exploring the integration of individual-based modeling and system dynamics. *Sandia National Laboratories*. Available online: http://www.sandia.gov/casosengineering/docs/SD_202011, p.20.
- Kumanyika, S.K., 2019. A framework for increasing equity impact in obesity prevention. *American journal of public health*, 109(10), pp.1350-1357. <https://doi.org/10.2105/AJPH.2019.305221>.

- Lee, B.Y., Bartsch, S.M., Mui, Y., Haidari, L.A., Spiker, M.L. and Gittelsohn, J., 2017. A systems approach to obesity. *Nutrition reviews*, 75(suppl_1), pp.94-106. <https://doi.org/10.1093/nutrit/nuw049>.
- Lehnert, T., Sonntag, D., Konnopka, A., Riedel-Heller, S. and König, H.H., 2013. Economic costs of overweight and obesity. *Best practice & research Clinical endocrinology & metabolism*, 27(2), pp.105-115.
- Mattes, R., 2014. Energy intake and obesity: ingestive frequency outweighs portion size. *Physiology & behavior*, 134, pp.110-118. <https://doi.org/10.1016/j.physbeh.2013.11.012>.
- Morshed, A.B., Kasman, M., Heuberger, B., Hammond, R.A. and Hovmand, P.S., 2019. A systematic review of system dynamics and agent-based obesity models: evaluating obesity as part of the global syndemic. *Obesity Reviews*, 20, pp.161-178. <https://doi.org/10.1111/obr.12877>.
- Mozaffarian, D., 2016. Dietary and policy priorities for cardiovascular disease, diabetes, and obesity: a comprehensive review. *Circulation*, 133(2), pp.187-225. <https://doi.org/10.1161/CIRCULATIONAHA.115.018585>.
- Must, A., Spadano, J., Coakley, E.H., Field, A.E., Colditz, G. and Dietz, W.H., 1999. The disease burden associated with overweight and obesity. *Jama*, 282(16), pp.1523-1529. <https://doi.org/10.1001/jama.282.16.1523>.
- Papadopoulos, S. and Brennan, L., 2015. Correlates of weight stigma in adults with overweight and obesity: A systematic literature review. *Obesity*, 23(9), pp.1743-1760. <https://doi.org/10.1002/oby.21187>
- Park, B.Z., Cantrell, L., Hunt, H., Farris, R.P., Schumacher, P. and Bauer, U.E., 2017. State public health actions to prevent and control diabetes, heart disease, obesity and associated risk factors, and promote school health. *Preventing Chronic Disease*, 14, p.E127. <https://doi.org/10.5888/pcd14.160437>.
- Penn, M., 2014. *The Importance of Primary Care Physicians*. Health and Wellness.
- Pi-Sunyer, X., 2009. The medical risks of obesity. *Postgraduate medicine*, 121(6), pp.21-33. <https://doi.org/10.3810/pgm.2009.11.2074>.
- Puhl, R.M. and Heuer, C.A., 2009. The stigma of obesity: a review and update. *Obesity (19307381)*, 17(5). <https://doi.org/10.1038/oby.2008.636>.
- Roberts, N., Li, V., Atkinson, J.A., Heffernan, M., McDonnell, G., Prodan, A., Freebairn, L., Lloyd, B., Nieuwenhuizen, S., Mitchell, J. and Lung, T., 2019. Can the target set for reducing childhood overweight and obesity be met? A system dynamics modelling study in New South Wales, Australia. *Systems Research and Behavioral Science*, 36(1), pp.36-52. <https://doi.org/10.1002/sres.2555>.
- Selvin, E., Parrinello, C.M., Sacks, D.B. and Coresh, J., 2014. Trends in prevalence and control of diabetes in the United States, 1988–1994 and 1999–2010. *Annals of internal medicine*, 160(8), pp.517-525. <https://doi.org/10.7326/M13-241>.
- Sterman, J.D., 1994. Learning in and about complex systems. *System dynamics review*, 10(2-3), pp.291-330. <https://doi.org/10.1002/sdr.4260100214>
- Suehs, B.T., Kamble, P., Huang, J., Hammer, M., Bouchard, J., Costantino, M.E. and Renda, A., 2017. Association of obesity with healthcare utilization and costs in a Medicare population. *Current Medical Research and Opinion*, 33(12), pp.2173-2180. <https://doi.org/10.1080/03007995.2017.1361915>.

- Thompson, D. and Wolf, A.M., 2001. The medical-care cost burden of obesity. *Obesity reviews*, 2(3), pp.189-197. <https://doi.org/10.1046/j.1467-789x.2001.00037.x>
- Thorpe, K.E., Florence, C.S., Howard, D.H. and Joski, P., 2004. The impact of obesity on rising medical spending. *Health Affairs*.
- Trogdon, J.G., Finkelstein, E.A., Hylands, T., Dellea, P.S. and Kamal-Bahl, S.J., 2008. Indirect costs of obesity: a review of the current literature. *Obesity reviews*, 9(5), pp.489-500. <https://doi.org/10.1111/j.1467-789X.2008.00472.x>.
- van Baal, P.H.M., Polder, J.J., De Wit, G.A., Hoogenveen, R.T., Feenstra, T.L., Boshuizen, H.C., Engelfriet, P.M. and Brouwer, W.B.F., 2008. Lifetime medical costs of obesity: prevention no cure for increasing health expenditure. *PLoS medicine*, 5(2), p.e29. <https://doi.org/10.1371/journal.pmed.0050029>.
- Waterlander, W.E., Singh, A., Altenburg, T., Dijkstra, C., Luna Pinzon, A., Anselma, M., Busch, V., van Houtum, L., Emke, H., Overman, M.L. and Chinapaw, M.J., 2021. Understanding obesity-related behaviors in youth from a systems dynamics perspective: the use of causal loop diagrams. *Obesity reviews*, 22(7), p.e13185. <https://doi.org/10.1111/obr.13185>.
- Williams, E.P., Mesidor, M., Winters, K., Dubbert, P.M. and Wyatt, S.B., 2015. Overweight and obesity: prevalence, consequences, and causes of a growing public health problem. *Current obesity reports*, 4(3), pp.363-370. <https://doi.org/10.1007/s13679-015-0169-4>.
- World Health Organization, 2000. Obesity: preventing and managing the global epidemic: Report of a WHO consultation. *WHO Technical Report Series*, No. 894. World Health Organization, Geneva, Switzerland. <https://iris.who.int/handle/10665/42330>
- Xue, H., Slivka, L., Igusa, T., Huang, T.T. and Wang, Y., 2018. Applications of systems modelling in obesity research. *Obesity Reviews*, 19(9), pp.1293-1308. <https://doi.org/10.1111/obr.12695>.
- Yusefzadeh, H., Rashidi, A. and Rahimi, B., 2019. Economic burden of obesity: A systematic review. *Asian Journal of Social Health and Behavior*, 2(1), pp.7-12. https://doi.org/10.4103/SHB.SHB_37_18.
- Zainal Abidin, N., Mamat, M., Dangerfield, B., Zulkepli, J.H., Baten, M.A. and Wibowo, A., 2014. Combating obesity through healthy eating behavior: a call for system dynamics optimization. *PLoS One*, 9(12), p.e114135. <https://doi.org/10.1371/journal.pone.0114135>.
- Zare, M.Y., 2012. A system dynamics approach to healthcare cost control. *International Journal of Industrial Engineering & Production Research*, 23(3), pp.175-185.
- Zhao, W., Zhai, Y., Hu, J., Wang, J., Yang, Z., Kong, L. and Chen, C., 2008. Economic burden of obesity-related chronic diseases in Mainland China. *Obesity reviews*, 9, pp.62-67. <https://doi.org/10.1111/j.1467-789X.2007.00440.x>.



Mitigating Iran's Electricity Deficit through Household Photovoltaic Expansion: A System Dynamics Approach with Impact Analysis on CO₂ Emissions and Water Resources

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ABSTRACT

This study employs System Dynamics modeling to assess the expansion of household photovoltaic (PV) systems as a strategy to mitigate Iran's electricity deficit, which is exacerbated by urban air pollution, reliance on fossil fuels, and natural gas shortages. By evaluating five investment allocation scenarios between household PV and thermal power plants, the findings indicate that an optimal configuration consists of a 75% PV and 25% thermal power split. Under this scenario, the capacity deficit is reduced to 5.6 GW by 1412, significantly outperforming conventional thermal expansion, which results in a 25.2 GW shortfall. By 1430, this policy enables PV generation to reach 457.6 TWh, supplying 58.9% of total electricity demand while reducing CO₂ emissions by 69.8 million tons and water consumption by 340.1 billion m³. These improvements contribute to enhanced air quality, reduced water scarcity, and decreased dependence on natural gas. Nevertheless, the results reveal that even extensive PV deployment cannot fully satisfy long-term electricity demand, with a projected shortfall of 15.4 GW by 1430 under the optimal scenario. While household PV systems offer substantial short- and mid-term advantages, a holistic energy strategy incorporating diverse solutions remains essential to ensuring Iran's long-term energy security.

Keywords

Energy Imbalance, Household Photovoltaic, Energy Policy, CO₂ emission reduction, Water resource management, System dynamics.

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1. Introduction

Electricity is a fundamental pillar of modern civilization, essential for socio-economic development, technological progress, and quality of life. Reliable electricity supply underpins industrial productivity, economic growth, and social stability, aligning with the United Nations Sustainable Development Goals (UN-SDGs), particularly Goal 7, which advocates for universal access to affordable, reliable, and sustainable energy by 2030 ([Audinet et al., 2010](#); [Danso-Wiredu et al., 2016](#); [Doroodi et al., 2024](#); [Khan et al., 2020](#); [Mahbub, 2023](#); [Mukhtar et al., 2021](#); [Zhang et al., 2024](#)). In developed nations, electricity consumption closely correlates with economic expansion, acting as a catalyst for prosperity (Bank, 2010; [Danso-Wiredu et al., 2016](#); [Vasconcelos et al., 2021](#)).

Despite its abundant fossil fuel reserves and significant renewable energy potential, Iran faces critical challenges in its electricity sector. The country's heavy reliance on fossil fuels—primarily natural gas and oil, which constitute 88.1% of the energy mix—has become increasingly unsustainable as surging demand outpaces supply ([Asadi et al., 2023](#)). In the current Iranian year alone, electricity demand has risen by 6,000 megawatts (MW), pushing peak consumption to approximately 80,000 MW, while supply struggles to keep pace, resulting in a peak deficit of up to 18,000 MW ([EnergyPress, 2024](#); [Tehran Times, 2024](#)).

This electricity crisis is exacerbated by several factors, including aging power generation infrastructure—many plants exceed 30 years in operation—leading to inefficiencies, high maintenance costs, and operational losses. Additionally, energy subsidies encourage excessive consumption while discouraging investment in efficient technologies and renewable energy ([Aryanpur et al., 2019](#); [Tofigh and Abedian, 2016](#)). Despite a nominal generation capacity of around 90,000 MW, actual output remains significantly lower at approximately 75,000 MW due to inefficiencies and transmission losses of about 13% ([Asadi et al., 2023](#); [Tehran Times, 2024](#); [Shokri, 2024](#)).

The industrial sector bears the brunt of these shortages, with potential annual losses estimated between \$6 billion and \$8 billion due to production disruptions ([News.Az, 2024](#); [Shokri, 2024](#)). Furthermore, power shortages disrupt essential services such as healthcare and education, contributing to economic instability. According to World Bank studies, power disruptions can reduce economic growth by 2% and GDP by approximately 7% ([Fisher-Vanden et al., 2012](#); [Usman, 2022](#); [Zhang, 2018](#)). Although Iran possesses favorable conditions for renewable energy, its share in electricity generation remains below 1%, highlighting a missed opportunity for diversification ([Shokri, 2024](#)).

Addressing these challenges requires a comprehensive transformation of Iran's energy policy. Key priorities include diversifying the energy mix by integrating renewable sources, improving efficiency through technological advancements and demand management, reforming energy pricing structures, and enhancing financial stability to attract private investment (Aryanpur et al., 2019; Tofigh and Abedian, 2016). A sustainable energy strategy that integrates household-level renewable solutions is crucial for mitigating Iran's electricity deficit while promoting economic growth and environmental sustainability.

This study examines the expansion of household photovoltaic (PV) systems as a viable solution, employing a system dynamics approach to model Iran's electricity sector. The system dynamics framework effectively captures the intricate interactions and feedback loops within energy systems, enabling a dynamic understanding of household PV adoption, infrastructure limitations, and policy interventions (Balázs et al., 2024; Roybal and Jeffers, 2013).

The study's goals are to (1) identify the key factors contributing to electricity deficits, with a focus on household consumption, (2) develop a system dynamics model that incorporates the impact of PV systems, (3) assess the effectiveness of policy measures such as incentives for PV installation and energy efficiency programs, and (4) propose long-term scenarios that highlight the role of household PV systems in mitigating electricity imbalance. This analysis aims to provide actionable recommendations for promoting household PV adoption as a cornerstone of sustainable electricity management in Iran.

The paper is organized as follows: Section 2 reviews electricity imbalances in Iran, the role of system dynamics, global renewable energy integration, research gaps in household photovoltaics, and the study's contribution. Section 3 outlines the methodology, including causal loop diagrams, stock and flow diagrams, investment redistribution, and environmental analysis. Section 4 presents the results, validation through behavior tests, and policy assessment. Section 5 concludes with findings and recommendations for addressing Iran's electricity challenges.

2. Literature review

The challenge of electricity deficits has been extensively studied, with various solutions proposed to enhance energy security. As shown in Table 1, which summarizes key literature in this field, researchers have approached this problem from multiple angles, including power shortage resilience, demand-side management, sustainable power system transitions, and renewable energy integration.

Research highlights that distributed photovoltaic (PV) generation can enhance energy resilience, reduce reliance on fossil fuels, and contribute to reductions in greenhouse gas (GHG) emissions. Karbasioun's study ([Karbasioun et al., 2023](#)), which applied System Dynamics modeling and Multi-Criteria Decision Analysis, examined Iran's sustainable power system transition over the 2016–2040 period. It prioritized combined cycle systems and water-efficient renewable technologies to address concerns about efficiency and water scarcity.

Studies on energy transitions in fossil-fuel-rich countries emphasize the integration of decentralized renewable energy sources into existing grids. However, they often focus on large-scale renewable projects rather than addressing immediate electricity deficits at the household level ([Allasseri et al., 2017](#)). Allasseri's research on Kuwait specifically recommended Incentive-Based Demand Response Programs (IBDRP) as more suitable than price-based programs due to the country's low, flat electricity rates.

Economic and environmental dispatch models have been explored to optimize the integration of renewable energy sources while maintaining grid stability. Pazheri's study in Malaysia investigated optimal energy dispatch strategies in renewable-rich areas using an optimization model that considered the integration of renewable energy and storage. However, financial barriers and the lack of regulatory frameworks continue to hinder the adoption of large-scale household PV ([Pazheri et al., 2012](#)). [Hsu \(2012\)](#) examined the effectiveness of feed-in tariffs in promoting the adoption of renewable energy in Taiwan using System Dynamics modeling. While these studies acknowledge the benefits of renewable energy, they do not specifically focus on household PV systems as a direct solution to electricity deficits, leaving a critical gap in understanding their role in mitigating shortages in countries like Iran.

System Dynamics (SD) modeling has been widely applied to energy planning, particularly in assessing policy impacts and supply-demand dynamics. As evident from Table 1, multiple studies on Iran's electricity sector have employed SD approaches ([Doroodi et al., 2024](#)). [Doroodi et al. \(2024\)](#) evaluated long-term policy interventions on renewable energy deployment and fossil fuel consumption through 2040 using SD modeling combined with the Taguchi Design of Experiments for parameter optimization. Their study examined the impact of various factors, including export price, import cost, carbon damage, and budget allocation, on the economic and environmental sustainability of Iran's electricity industry.

Electricity subsidy policies have been studied to understand their effects on overconsumption and inefficiencies in power plant operations, highlighting the need for pricing reforms ([Dehghan et al., 2021](#)). Dehghan's research analyzed the impact of capacity payment mechanisms on

generation capacity expansion decisions using SD modeling to simulate market behavior. In a subsequent study, [Dehghan et al. \(2022\)](#) proposed a Stackelberg game model for coordinating generation capacity expansion decisions, taking into account both electricity market competition and natural gas consumption optimization.

Scenario-based SD modeling has also been used to propose an 80% allocation of capacity development to renewable sources, demonstrating a significant reduction in CO₂ emissions ([Doroodi et al., 2024](#)). [Kachoei et al. \(2018\)](#) specifically addressed electricity demand and supply in Iran through 2040, using econometric methods for demand modeling and the LEAP model for supply simulation. They recommended policies to promote renewable energy development and decrease reliance on fossil fuels. However, these studies largely focus on energy transition strategies rather than addressing the immediate and growing electricity deficit, particularly through decentralized solutions such as household PV expansion.

The environmental and economic benefits of household PV adoption have been well documented. Large-scale PV deployment can help alleviate urban air pollution and mitigate the effects of climate change by replacing fossil fuel-based electricity generation ([Masoomi et al., 2022](#)). Masoomi's research, which utilized the LEAP software for demand simulation and supply optimization through 2035, highlighted that implementing demand-side management reduces social costs and emissions from thermal power plants, thereby contributing to economic, social, and environmental sustainability. In Iran, where water-intensive thermal power plants dominate the energy mix, shifting towards solar PV can substantially reduce water consumption. Studies emphasize the need for government incentives and consumer engagement to promote the adoption of renewable energy ([Allasseri et al., 2017](#)). However, there is a lack of research directly evaluating household PV as a targeted solution to Iran's electricity deficit.

Other relevant studies in Table 1 include power shortage resilience planning ([Olausson, 2019](#)), which recommended improvements to Sweden's STYREL planning system, and research on micro-combined heat and power in Great Britain's residential sector ([Ben Maalla and Kunsch, 2008](#)), which assessed the market penetration potential of this technology. [Fasihzadeh et al. \(2014\)](#) developed simulation algorithms to improve the operation of gas transmission networks in Iran, though their work focused specifically on natural gas rather than electricity.

This study addresses this critical gap by developing a System Dynamics model to assess household PV expansion as a direct solution to Iran's electricity deficit. Unlike previous research that primarily examines large-scale energy policies, this study focuses on how household PV adoption can effectively mitigate supply shortages. By integrating electricity

supply-demand dynamics, technical constraints, and socio-economic factors, this research offers a novel perspective on utilizing decentralized renewable energy to address electricity deficits, rather than solely transitioning to renewables for long-term sustainability.

As indicated in Table 1, this study examines the 1404–1430 (2025–2052) time horizon in Iran, specifically focusing on household PV systems and thermal power plants using System Dynamics modeling. This study will present the optimal policy recommendation for financial investment, aiming to mitigate the capacity deficit. Additionally, the inclusion of an environmental analysis enhances the understanding of how household PV adoption contributes to sustainable electricity management. By filling this gap, this research aims to provide actionable insights into how household PV systems can serve as a key component in reducing Iran's electricity deficit while complementing broader energy policies.

In Table 1, the explanation of the "Purpose of the Model" column is as follows:

1. **Power shortage:** Does the model address issues related to electricity shortages or deficits?
2. **Supply-side management:** Does the model focus on managing and optimizing electricity generation and supply?
3. **Demand-side management:** Does the model consider strategies to influence and manage electricity consumption?
4. **Technical:** Does the model primarily address technical aspects of the electricity system, such as infrastructure and technology?
5. **Economic:** Does the model analyze economic factors related to electricity, such as costs, pricing, and investment?
6. **Environmental:** Does the model assess the environmental impacts of electricity generation and consumption?
7. **Social:** Does the model consider social implications related to electricity access, affordability, and equity?
8. **Renewable Energy and Pricing Integration:** Does the model examine the integration of renewable energy sources and their impact on electricity pricing?

Table 1. Overview of key studies on electricity deficits, renewable integration, and system dynamics modeling

Study Reference	Focus Area	Recommended Policy/Result	Methodology & Tools	Carriers/ Technologies Sector	Case Study	Time Horizon	Purpose of the Model* (Yes/No)							
							1	2	3	4	5	6	7	8
(Olausson, 2019)	Power shortage resilience planning	STYREL planning system improvements: - Increased resource allocation for local coordinators. - Enhanced feedback mechanisms for improved system trust and effectiveness. Implementation of Incentive-Based Demand Response Programs (IBDRP):	Document analysis, interviews, and surveys of local and regional coordinators.	Electricity	Sweden	Not specified	✓	×	×	✓	×	×	✓	×
(Alasser et al., 2017)	Demand-Side Management (DSM) in electricity markets	- Due to Kuwait's low, flat electricity rates, Price-Based Demand Response Programs (PBD RP) are unsuitable. - IBDRP offers a more viable solution for reducing peak load and energy consumption.	Literature review and SWOT analysis of various DSM subcategories, including DR and IBDRP.	Electricity	Kuwait	Not specified	×	✓	✓	×	×	✓	×	×
(Karbasioun et al., 2023)	Sustainable power system transition in fossil fuel-rich countries	Prioritize combined cycle systems: Enhancing current energy system efficiency through the implementation of combined cycle systems is crucial. Implement water-efficient renewable technologies to address concerns about water scarcity.	SD modeling, Multi-Criteria Decision-Analysis (MCDA) using AHP-TOPSIS.	Electricity, Renewable Energy	Iran	2016-2040	×	×	×	✓	✓	✓	✓	✓
(Masoomi et al., 2022)	Demand-Side Management (DSM) for sustainability in Iran's electricity sector	Optimize electricity supply and demand: Implementing DSM reduces social costs and emissions from thermal power plants. - This contributes to economic, social, and environmental sustainability.	LEAP software for demand simulation and supply optimization, incorporating emission limit scenarios.	Electricity	Iran	Until 2035	×	×	✓	×	✓	✓	×	×
(Kachoe et al., 2018)	Electricity demand and supply in Iran	Develop renewable technologies: To reduce fossil fuel reliance and carbon emissions, implement policies that promote the development of renewable energy.	Econometric methods for demand modeling, the LEAP model for supply simulation under various scenarios.	Electricity, Renewable Energy	Iran	Until 2040	×	×	×	×	✓	✓	×	✓
(Ben Maalla and Kunsch, 2008)	Micro-combined heat and power (m-CHP) in the residential sector	The study focuses on assessing the potential of m-CHP technology.	System dynamics model to analyze the market penetration of m-CHP and forecast future installations.	Natural gas, electricity (m-CHP with Stirling engines)	Great Britain	Not specified	×	×	×	✓	✓	×	×	×

Study Reference	Focus Area	Recommended Policy/Result	Methodology & Tools	Carriers/ Technologies Sector	Case Study	Time Horizon	Purpose of the Model* (Yes/No)							
							1	2	3	4	5	6	7	8
(Pazheri et al., 2012)	Economic and Environmental Dispatch in Renewable-Rich Areas	Investigate optimal energy dispatch strategies, including economic and environmental considerations, in areas with significant renewable energy potential.	Optimization model for economic and ecological dispatch, considering the integration of renewable energy and storage.	Electricity, Renewable Energy (solar, wind)	Malaysia (renewable-rich area)	Not specified	x	x	x	x	✓	✓	x	✓
(Fasihizadeh et al., 2014)	Natural Gas (NG) transmission network optimization in Iran	Develops simulation algorithms to improve the operation of gas transmission networks.	Simulation modeling using algorithms for optimizing gas transmission network operations.	Natural gas	Iran	Not specified	x	x	x	✓	x	x	x	x
(Dehghan et al., 2021)	Generation Capacity Expansion in Iran's Electricity Market	Analyzes the impact of capacity payment mechanisms on generation capacity expansion decisions, considering both short-term and long-term market dynamics.	SD modeling to simulate market behavior and capacity expansion decisions.	Electricity (includes thermal, hydro, and renewable sources)	Iran	Not specified	x	✓	✓	✓	✓	✓	x	✓
(Dehghan et al., 2022)	Sustainable Electricity Supply and Natural Gas Consumption Optimization in Iran	Proposes a Stackelberg game model for coordinating generation capacity expansion decisions, considering both electricity market competition and natural gas consumption optimization. Investigates the influence of various factors (export price, import cost, carbon damage, budget allocation) on the economic and environmental sustainability of Iran's electricity industry.	Bilevel optimization using the Stackelberg game model, considering electricity market dynamics and natural gas constraints.	Electricity (thermal, hydro, renewable) and Natural Gas	Iran	Not specified	x	✓	x	✓	✓	✓	x	x
(Doroodi et al., 2024)	Sustainable Electricity Industry Growth in Iran	Investigates the influence of various factors (export price, import cost, carbon damage, budget allocation) on the economic and environmental sustainability of Iran's electricity industry.	SD modeling combined with Taguchi Design of Experiments (TDOE) for parameter optimization.	Electricity (thermal, hydro, renewable)	Iran	Until 2040	x	x	x	x	✓	✓	x	✓
(C. W. Hsu, 2012)	Renewable energy development in Taiwan	Evaluates the effectiveness of feed-in tariffs (FITs) in promoting renewable energy adoption in Taiwan.	SD modeling to simulate the impact of FITs on renewable energy investments.	Renewable Energy (solar PV)	Taiwan	Not specified	x	x	x	x	✓	x	x	✓
This study	Mitigating Iran's electricity deficit through household photovoltaic expansion	Optimal policy for financial investment reduces capacity deficit	SD modeling	Household PV systems, thermal power plants	Iran	1404–1430 (2025–2052)	✓	✓	✓	✓	✓	✓	x	✓

3. Research methodology and framework

The research methodology employed in this study consists of five key steps:

1. **Data Collection:** Relevant data were gathered based on the research questions to provide a structured foundation for the study.
2. **Case Study Selection and Policy Identification:** A case study was selected, and multiple policy scenarios were identified for analysis.
3. **Policy Design:** The identified policies were developed and structured to align with the study's objectives.
4. **Model Development:** A comprehensive modeling framework was designed and constructed, incorporating environmental factors for policy evaluation.
5. **Model Validation:** The gathered data were utilized to test, validate, and refine the developed model, ensuring its reliability and accuracy.

To simplify real-world complexities, this study incorporated several assumptions. These assumptions include:

- The system's primary variables were validated using a Structurally Oriented Behavior Test-Behavior Reproduction over 20 years, from 2005 to 2024 (corresponding to the years 1384 to 1403).
- It is assumed that over time, advancements in science and technology will reduce energy-related investment costs. However, for this study, investment costs were kept constant over the 27 years, maintaining the value from the first year.
- The model was designed to evaluate conditions in the medium term, focusing on a 27-year horizon from 1404 to 1430 (2025–2052), as it is anticipated that global policies will change after 2052. All costs are expressed in US dollars (USD), based on fixed values from 1394 (2015).
- Technological improvements in transformation and refinement were assumed to be integrated with the average characteristics of Iran's energy system.
- Due to Iran's limited nuclear power capacity (10,000 MW) and slow development, nuclear power plants were excluded from the model. Additionally, this study focuses only on household photovoltaic systems, leaving the development of other renewable energy sources outside the scope.
- All domestic energy consumption, both renewable and non-renewable, was included in the calculations.
- Thermal recycling and cogeneration systems were excluded due to their limited implementation and minimal impact on energy production in Iran.

To gather the necessary data for model design and implementation, this study relied on various sources, including journals, the World Bank, the International Energy Agency (IEA), the Intergovernmental Panel on Climate Change (IPCC), the U.S. Energy Information Administration (EIA), as well as local references such as the Ministry of Energy, the Ministry of Petroleum, and the Central Bank of Iran. The datasets used for restructuring and evaluating the study's results can be made available upon request.

3.1. Dynamics hypothesis, causal loop diagrams, and stock and flow diagrams

The causal loop diagram (CLD) in Figure 1 outlines the structure of Iran's electricity system, consisting of two main components: Total electricity demand and Total power generation. The difference between these two variables, the Power deficit, is the central focus of this study. Also, the stock and flow diagrams (SFD) of Iran's power industry are presented, with Figure 2 illustrating the technical modeling and policy implementation related to the power deficit issue, and Figure 3 highlighting the environmental analysis used to compare policy alternatives. The feedback loops incorporated into the System Dynamics (SD) model are detailed in Table 2.

Table 2. Loops in the system dynamics modeling of the power generation industry of the study

Loop Type	Loop number	Loop name
Reinforcing	R1 ¹	Population
	R2	Household Demand Propensity for Electricity
	R3	GDP
	R4	Natural Gas Consumption and Thermal Power Plant Generation
Balancing	B1 ²	Total Electricity Demand and Power Deficit
	B2	Price-Driven Household Electricity Demand
	B3	Production and Services Electricity Demand
	B4	Thermal Power Plant Capacity
	B5	Natural Gas Production Capacity
	B6	Household PV Capacity
	B7	Investment Absorbed for Household PV Expansion for Compensate Power Deficit
	B8	Investment Absorbed for Thermal Power Plant Expansion for Compensate Power Deficit (or Total Electricity Supply and Power Deficit)

¹ R: Reinforcing Loop

² B: Balancing Loop

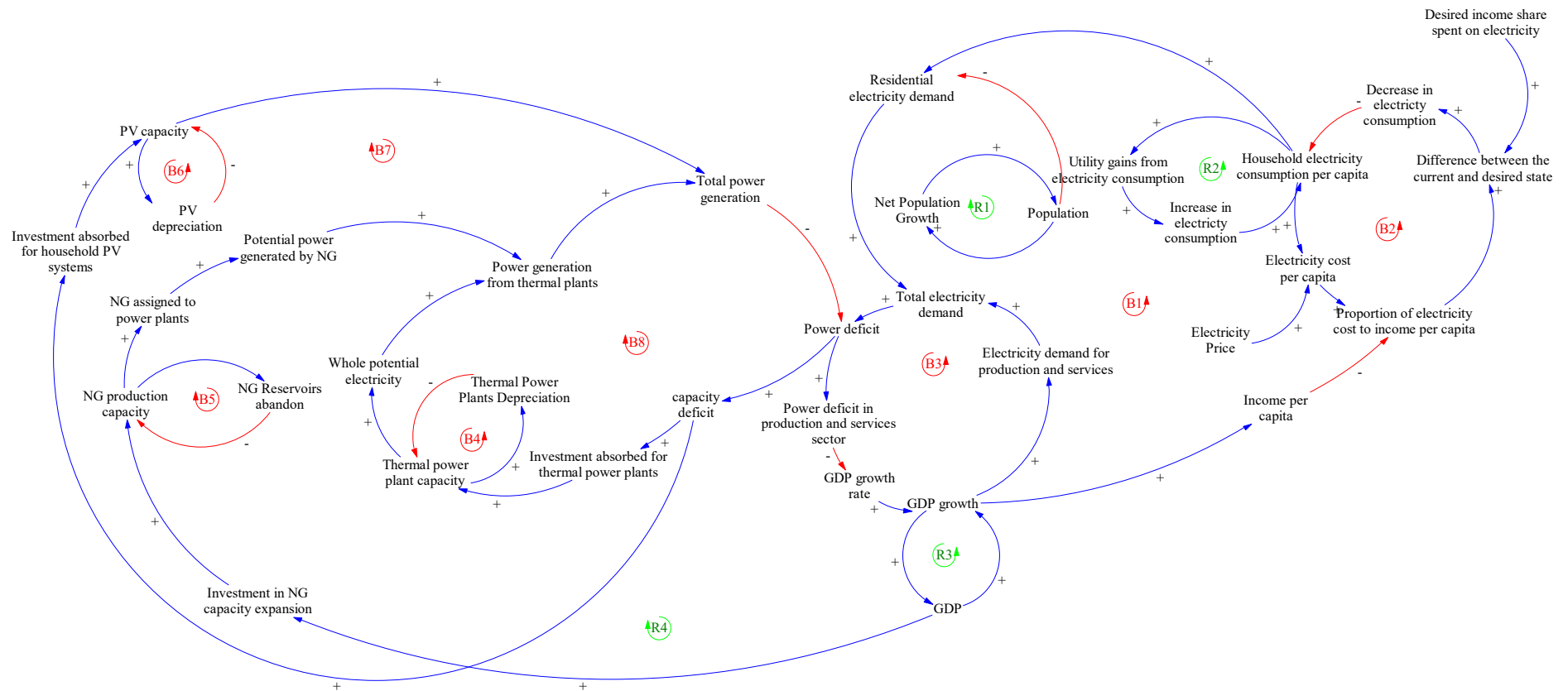


Figure 1. Casual loop diagram (CLD) of Iran's power industry highlighting the power deficit challenge

Technical Modeling & Policy Implementation

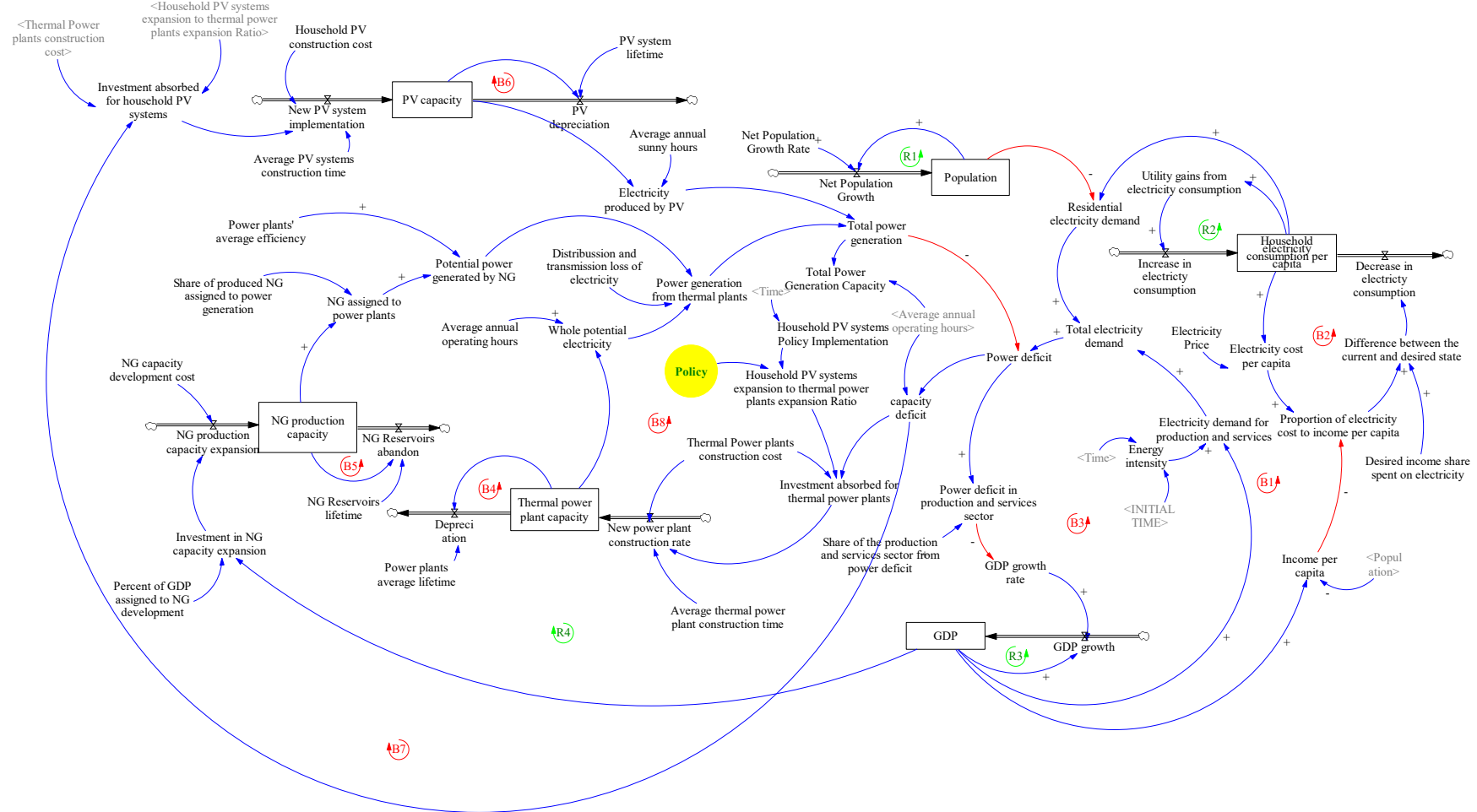


Figure 2. Stock and flow diagram (SFD) of Iran's power industry highlighting the power deficit issue - technical modeling, and policy implementation

Environmental Analysis

CO2 Emission

Water Consumption

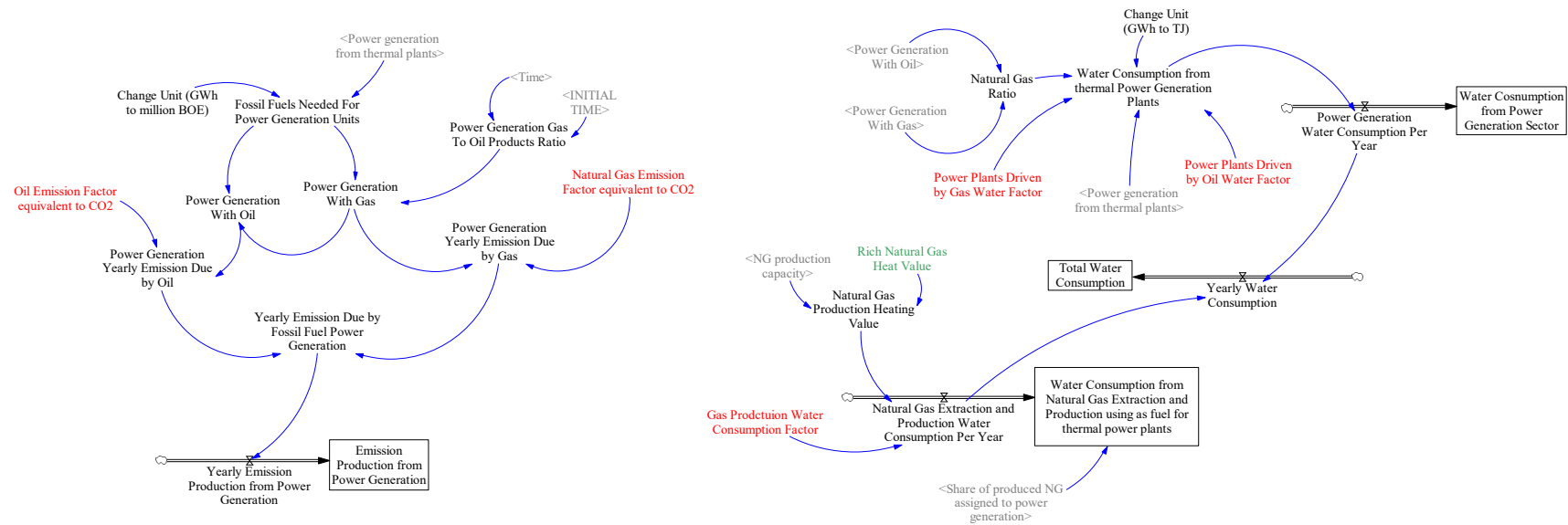


Figure 3. Stock and flow diagram (SFD) for environmental analysis for comparing policy alternatives

The relevant equations for this section are (1) to (3).

$$\text{Power deficit} = \text{IF THEN ELSE} (\text{Total electricity demand} < \text{Total power generation}, 0, \text{Total electricity demand} - \text{Total power generation}) \text{ [GWh]} \quad (1)$$

$$\text{Total electricity demand} = \text{Electricity demand for production and services} + \text{Residential electricity demand} \text{ [GWh]} \quad (2)$$

$$\text{Total power generation} = \text{Electricity produced by PV} + \text{Power generation from thermal plants} \text{ [GWh]} \quad (3)$$

Electricity demand is modeled across two main sectors: household demand and demand for production and services. Due to their distinct characteristics, separate models are constructed for each of them. Household electricity consumption is influenced by factors such as population growth (R1), electricity prices, and per capita income. Two feedback loops govern this sector: the reinforcing loop (R2), reflecting the tendency of households to increase electricity consumption to maximize utility, and the balancing loop (B2), as electricity prices and income constraints limit demand growth. Consumer theory helps explain these dynamics by modeling household behavior under the principles of utility maximization. In the reinforcing loop (R2), households allocate resources to electricity consumption as it enhances their utility, driven by the marginal utility derived from using appliances or maintaining comfort. However, as part of the balancing loop (B2), households face budget constraints that require trade-offs between electricity and other expenditures. Rising electricity prices reduce the relative affordability of electricity, while per capita income determines the extent to which these constraints can be managed. By evaluating the gap between the desired and actual income shares allocated to electricity, household adjust their consumption patterns, either by reducing usage or seeking efficiency improvements, thereby introducing mechanisms to regulate excessive usage and achieve a new consumer equilibrium. The relevant equations for this section are (4) to (12).

$$\text{Population} = \int (\text{Net Population Growth}) + 7.01826 \times 10^7 \text{ [Person]} \quad (4)$$

$$\text{Net Population Growth} = \text{Population} * \text{Net Population Growth Rate} \text{ [Person/Year]} \quad (5)$$

$$\text{Household electricity consumption per capita} = \int (\text{Increase in electricity consumption} - \text{Decrease in electricity consumption}) + 0.000628479 \text{ [GWh/Person]} \quad (6)$$

$$\text{Utility gains from electricity consumption} = 1 - (0.8 * (\text{EXP} (-0.5 * \text{Household electricity consumption per capita}))) \text{ [1/Year]} \quad (7)$$

$$\text{Increase in electricity consumption} = \text{Utility gains from electricity consumption} * 0.00013 \text{ [GWh/Person/Year]} \quad (8)$$

$$\text{Electricity cost per capita} = \text{Household electricity consumption per capita} * \text{Electricity Price} \text{ [Billion Dollar]} \quad (9)$$

$$\text{Proportion of electricity cost to income per capita} = \text{Electricity cost per capita} / \text{Income per capita} \text{ [-]} \quad (10)$$

$$\text{Difference between the current and desired state} = \text{Proportion of electricity cost to income per capita/Desired income share spent on electricity [-]} \quad (11)$$

$$\text{Decrease in electricity consumption} = \text{IF THEN ELSE (Difference between the current and desired state} < 1, 0, ((\text{Difference between the current and desired state}/10) * 5e-05)) \quad (12)$$

[GWh/Person/Year]

The production and services demand sector includes industries, agriculture, commercial establishments, and public lighting. This demand is modeled using GDP as an energy intensity coefficient in loop (R3), as shown in equation (13).

$$\text{Electricity demand for production and services} = \text{GDP} * \text{Energy intensity [GWh]} \quad (13)$$

Additionally, according to equations (14) to (17), electricity deficits negatively impact GDP growth, forming a feedback loop (B3) where reduced GDP leads to decreased electricity demand.

$$\text{Power deficit in the production and services sector} = \text{Power deficit} * \text{Share of the production and services sector from power deficit [GWh/Year]} \quad (14)$$

$$\text{GDP growth rate} = 0.03 - ((\text{Power deficit in production and services sector}/10000) * 0.01) \quad (15)$$

[1/Year]

$$\text{GDP growth} = \text{GDP} * \text{GDP growth rate [Billion Dollars/Year]} \quad (16)$$

$$\text{GDP} = \int (\text{GDP growth}) + 333.229 \text{ [Billion Dollar]} \quad (17)$$

The interplay between Total Electricity Demand and Electricity Deficit is captured by the balancing loop B1, which reflects the effect of increasing demand on system capacity. Electricity generation in Iran relies heavily on fossil fuels, primarily natural gas. The supply side model incorporates investments in natural gas capacity expansion, driven by GDP growth (R4), to enhance the availability of natural gas for thermal power generation. However, the depletion of natural gas reserves over time is captured by the balancing loop B5, while the aging of thermal power plants impacts supply capacity, modeled through balancing loop B4. The relevant equations for this section are (18) to (28). In modeling power generation from thermal plants, the total output is determined by the lesser of two factors: the nominal capacity of the plants (the whole potential electricity) and the possible power generated based on the natural gas supplied as fuel. This approach accounts for the fact that either the plant's capacity or the available fuel supply can limit total generation. Additionally, electricity distribution and transmission losses are incorporated into the model.

$$\text{Investment in NG capacity expansion} = \text{GDP} * \text{Percent of GDP assigned to NG development [Billion Dollars]} \quad (18)$$

$$\text{NG production capacity expansion} = \text{Investment in NG capacity expansion} / \text{NG capacity development cost [million m}^3/\text{Year}] \quad (19)$$

$$\text{NG reservoirs depreciation} = \text{NG production capacity} / \text{NG Reservoirs lifetime [million m}^3/\text{Year}] \quad (20)$$

$$\text{NG production capacity} = \int (\text{NG production capacity expansion} - \text{NG reservoirs depreciation}) + 151018 \text{ [million m}^3] \quad (21)$$

$$\text{NG assigned to power plants} = \text{NG production capacity} * \text{Share of produced NG assigned to power generation [million m}^3] \quad (22)$$

$$\text{Potential power generated by NG} = \text{NG assigned to power plants} * \text{Power plants' average efficiency [GWh]} \quad (23)$$

$$\text{New power plant construction rate} = \text{Investment absorbed for thermal power plants} / (\text{Thermal Power plants construction cost} * \text{Average thermal power plant construction time}) \text{ [GW/Year]} \quad (24)$$

$$\text{Thermal power plants depreciation} = \text{Thermal power plant capacity} / \text{Power plants' average lifetime [GW/Year]} \quad (25)$$

$$\text{Thermal power plant capacity} = \int (\text{New power plant construction rate} - \text{Thermal power plants depreciation}) + 26.2441 \text{ [GW]} \quad (26)$$

$$\text{Whole potential electricity} = \text{Thermal power plant capacity} * \text{Average annual operating hours [GWh]} \quad (27)$$

$$\text{Power generation from thermal plants} = \text{MIN} (\text{Whole potential electricity}, \text{Potential power generated by NG}) * \text{Distribution and transmission loss of electricity [GWh]} \quad (28)$$

To address the electricity deficit, the study hypothesizes that government investments should align with forecasted deficits. The approach involves expanding both thermal power plants and household photovoltaic (PV) systems. The financial investment allocation is first calculated for the thermal power plants required to compensate for the electricity deficit. The policies then define how this total investment is redistributed between household PV systems and thermal power plants. The relevant equations for this section are (29) to (36).

$$\text{Household PV systems Policy Implementation} = \text{IF THEN ELSE}(\text{Time} > 1403, 1, 0) [-] \quad (29)$$

$$\text{Household PV systems expansion to thermal power plants expansion Ratio} = \text{Policy} * \text{Household PV systems Policy Implementation} [-] \quad (30)$$

$$\text{Investment absorbed for thermal power plants} = (\text{capacity deficit} * \text{Thermal Power plants construction cost}) * (1 - \text{Household PV systems expansion to thermal power plants expansion Ratio}) \text{ [Dollar]} \quad (31)$$

$$\text{Investment absorbed for household PV systems} = (\text{capacity deficit} * \text{Thermal Power plants construction cost}) * (\text{Household PV systems expansion to thermal power plants expansion Ratio}) \text{ [Dollar]} \quad (32)$$

$$\text{New PV system implementation} = \text{Investment absorbed for household PV systems} / (\text{Household PV construction cost} * \text{Average PV systems construction time}) \text{ [GW/Year]} \quad (33)$$

$$\text{PV depreciation} = \text{PV capacity} / \text{PV system lifetime [GW/Year]} \quad (34)$$

$$\text{PV capacity} = \int (\text{New PV system implementation} - \text{PV depreciation}) + 0 \text{ [GW]} \quad (35)$$

$$\text{Electricity produced by PV} = \text{Average annual sunny hours} * \text{PV capacity [GWh]} \quad (36)$$

For instance, Policy 2: a 25% investment in household PV systems and 75% in thermal power plants implies that 25% of the total financial investment initially earmarked for thermal power plants is instead allocated to household PV systems, leaving 75% for thermal power plant expansion. The study examines five policy scenarios:

- **Policy 1:** 0% investment in household PV systems; 100% in thermal power plants.
- **Policy 2:** 25% investment in household PV systems; 75% in thermal power plants.
- **Policy 3:** 50% investment in both household PV systems and thermal power plants.
- **Policy 4:** 75% investment in household PV systems; 25% in thermal power plants.
- **Policy 5:** 100% investment in household PV systems; 0% in thermal power plants.

These policies account for the lifespans of thermal power plants (B4) and household PV systems (B6), as well as the delays inherent in constructing these systems. The balancing loop B7 captures the dynamics of investment absorbed for household PV expansion, while balancing loop B8 reflects the investment absorbed for thermal power plant expansion. Both loops model the effect of these investments on reducing the electricity deficit.

3.2. Benefits of redistributing financial investment

Redistributing financial investment between household photovoltaic (PV) systems and thermal power plants offers several significant benefits, particularly in addressing the electricity deficit and ensuring a more sustainable and efficient energy system:

3.2.1. Diversification of energy sources

Allocating a portion of the investment to household PV systems reduces the dependence on fossil fuel-based thermal power plants. This diversification enhances the resilience of the electricity supply by incorporating renewable energy sources, making the system less vulnerable to fluctuations in fuel availability or prices.

3.2.2. Reduction in greenhouse gas emissions

Household PV systems utilize solar energy, a clean and renewable source. Shifting investment toward PV systems reduces reliance on fossil fuels, significantly lowering carbon emissions and contributing to climate change mitigation efforts.

3.2.3. Improved energy access and decentralization

Investing in household PV systems enables decentralized energy production, bringing electricity closer to end-users. This decentralization enhances energy access, especially in remote or underserved areas, and reduces transmission and distribution losses commonly associated with centralized thermal power generation.

3.2.4. Long-term cost savings

The cost of PV systems per kilowatt of generated electricity has significantly decreased due to advancements in solar technology, making them increasingly economically viable. While the initial investment may still be higher compared to thermal power plants, PV systems offer substantial long-term savings due to their minimal operational and maintenance costs. Moreover, the absence of fuel costs in PV systems provides a significant advantage, as it eliminates exposure to fluctuations in fuel prices and ensures greater financial stability over time.

3.2.5. Enhanced energy security

Incorporating PV systems reduces the country's reliance on imported fuels and slows the depletion of domestic natural gas reserves. This shift enhances energy security by enabling the nation to meet its electricity demands more independently. Moreover, the natural gas saved from being used for electricity generation can be redirected toward more valuable applications, such as export for economic gain, use as a feedstock in petrochemical industries, or storage for future strategic purposes. This approach not only bolsters energy security but also maximizes the economic and strategic value of natural gas resources.

3.2.6. Support for energy transition goals

Allocating financial resources to PV systems aligns with global energy transition goals, supporting commitments to renewable energy adoption and achieving sustainability targets.

3.2.7. Economic and social benefits

The development and installation of PV systems can stimulate local economies by creating jobs in manufacturing, installation, and maintenance. It also promotes energy equity by enabling households to generate their own electricity, potentially reducing their utility bills and enhancing their financial well-being.

3.2.8. Mitigation of capacity expansion delays

Expanding thermal power plants often involves lengthy construction timelines and regulatory approvals. In contrast, PV systems can be deployed relatively quickly, providing a more immediate solution to mitigating electricity deficits.

By redistributing investments between thermal power plants and household PV systems, the proposed approach strikes a balance between addressing immediate electricity deficits and advancing long-term sustainability goals. This strategic allocation ensures a more robust, environmentally friendly, and cost-effective energy system for the country.

3.3. Environmental analysis

This study includes an environmental analysis to evaluate and compare different policies for developing household PV systems, primarily aimed at addressing the country's power deficit. Two key ecological factors are considered ([Karbasioun et al., 2023](#)):

3.3.1. Greenhouse gas emissions

The analysis accounts for emissions resulting from fuel consumption in thermal power plants. Emission calculations are based on the Intergovernmental Panel on Climate Change (IPCC) guidelines and are tailored to Iran's average emission factors. The relevant equations for this section are (37) to (41).

$$\text{Fossil Fuels Needed for Power Generation Units} = \text{Power generation from thermal plants} \times \text{Change Unit (GWh to million BOE)} \quad (37)$$

$$\text{Power Generation with Gas} = \text{Fossil Fuels Needed for Power Generation Units} \times \text{Power Generation Gas to Oil Products Ratio} \quad (38)$$

$$\text{Power Generation with Oil} = \text{Fossil Fuels Needed for Power Generation Units} - \text{Power Generation with Gas} \quad (39)$$

$$\text{Yearly Emission Production from Power Generation} = \text{Yearly Emission Due by Fossil Fuel Power Generation} + \text{Power Generation Yearly Emission Due by Oil} + \text{Power Generation Yearly Emission Due by Gas} \quad (40)$$

$$\text{Emission Production from Power Generation} = \int (\text{Yearly Emission Production from Power Generation}) + 0 \quad (41)$$

3.3.2. Water consumption

Total water usage is assessed by calculating the water footprint associated with the natural gas supply chain used as fuel for thermal power plants, as well as the water requirements during the construction and operational phases of these power plants. The relevant equations for this section are (42) to (49).

$$\text{Natural Gas Ratio} = \text{Power Generation with Gas} / (\text{Power Generation with Oil} + \text{Power Generation with Gas}) \quad (42)$$

$$\text{Water Consumption from thermal Power Generation Plants} = ((\text{Power generation from thermal plants}) \times \text{Change Unit (GWh to TJ)}) \times (\text{Natural Gas Ratio} \times \text{Power Plants Driven by Gas Water Factor} + (1 - \text{Natural Gas Ratio}) \times \text{Power Plants Driven by Oil Water Factor}) \times 1000 \quad (43)$$

$$\text{Water Consumption from Power Generation Sector} = \int (\text{Power Generation Water Consumption Per Year}) + 0 \text{ [million m}^3\text{]} \quad (44)$$

$$\text{Natural Gas Production Heating Value} = \text{Rich Natural Gas Heat Value} * \text{NG production capacity [TJ]} \quad (45)$$

$$\text{Natural Gas Extraction and Production Water Consumption Per Year} = \text{Gas Production Water Consumption Factor} * \text{Natural Gas Production Heating Value [million m}^3\text{/Year]} \quad (46)$$

$$\text{Water Consumption from Natural Gas Extraction and Production using as fuel for thermal power plants} = \int (\text{Natural Gas Extraction and Production Water Consumption Per Year}) \quad (47)$$

$$* \text{Share of produced NG assigned to power generation} + 0 \text{ [million m}^3\text{]}$$

$$\text{Yearly Water Consumption} = \text{Power Generation Water Consumption Per Year} + \text{Natural Gas Extraction and Production Water Consumption Per Year [million m}^3\text{/Year]} \quad (48)$$

$$\text{Total Water Consumption} = \int (\text{Yearly Water Consumption}) + 0 \text{ [million m}^3\text{]} \quad (49)$$

By examining these factors, the study provides a comprehensive environmental comparison of thermal power plant expansion versus the development of household PV systems. This approach highlights the potential environmental benefits of shifting investments towards PV systems, particularly in terms of reducing emissions and conserving water resources. These insights are crucial for formulating environmentally sustainable solutions to the country's power deficit challenge. Additionally, it is important to note that the exogenous variables used in this model are listed in Table 3.

Table 3. exogenous variables of the study

Exogenous variable	Value	Reference
Oil Emission Factor equivalent to CO2	0.449936 million Tons CO2 equivalent/ (million BOE*Year)	(Karbasioun et al., 2023)
Natural Gas Emission Factor equivalent to CO2	0.343553 million Tons CO2 equivalent/ (million BOE*Year)	(Karbasioun et al., 2023)
Power Plants Driven by Gas Water Factor	(1 + 267) * 1e-06 million m3/TJ	(Karbasioun et al., 2023)
Power Plants Driven by Oil Water Factor	(1+485) * 1e-06 million m3/TJ	(Karbasioun et al., 2023)
Rich Natural Gas Heat Value	0.0985 * 1000 TJ/million m3	(Karbasioun et al., 2023)
Gas Production Water Consumption Factor	2.2 * 1e-06 million m3/TJ	(Karbasioun et al., 2023)
Average PV systems construction time	1 Year	(Hoorayesh, 2021)
Household PV construction cost	4.5e+08 Dollar/GW	(Hoorayesh, 2021)
PV system lifetime	25Year	(Hoorayesh, 2021)
Average annual sunny hours	2000 GWh/GW	(techsunsanat, n.d.)
Net Population Growth Rate	0.0145 1/Year	Experts' comments
Desired income share spent on electricity	0.02 Dmnl	Experts' comments
Electricity Price	6000 dollars/GWh	Experts' comments
Share of the production and services sector from the power deficit	0.1 1/Year	Experts' comments
Distribution and transmission loss of electricity	0.15	(“Barghnews,” 2019.)
Average annual operating hours	6800 GWh/GW	(Karbasioun et al., 2023)
Thermal Power plants construction cost	8.4e+08 Dollar/GW	(Foroutan, 2024)
Average thermal power plant construction time	3 Year	(Karbasioun et al., 2023)
Power plants' average lifetime	30 Year	(Karbasioun et al., 2023)
Percent of GDP assigned to NG development	0.0004 Dmnl	Experts' comments
NG Reservoirs lifetime	150 Year	(khabaronline,2011 n.d.)
NG capacity development cost	1/ (141*365) Billion Dollars/million cubic meter	(Shana, 2025)
Share of produced NG assigned to power generation	0.275 Dmnl	(Safari Dehkordi, 2024)
Power plants' average efficiency	0.35	(Karbasioun et al., 2023)

4. Results and discussion

4.1. Extreme condition test

In this test, the model's outputs should exhibit logical behavior when subjected to extremely large and small input values within its boundary conditions (Stermann, 2000). This approach was applied to assess the impact of *Electricity Price* on *Residential Electricity Demand*. Specifically, when the *Electricity Price* parameter increased from 6,000 (as shown in Table 3) to 10,000,000 \$/GWh (approaching an infinitely high value), the *Residential Electricity Demand* declined to nearly zero, demonstrating expected system behavior as depicted in Figure 4.

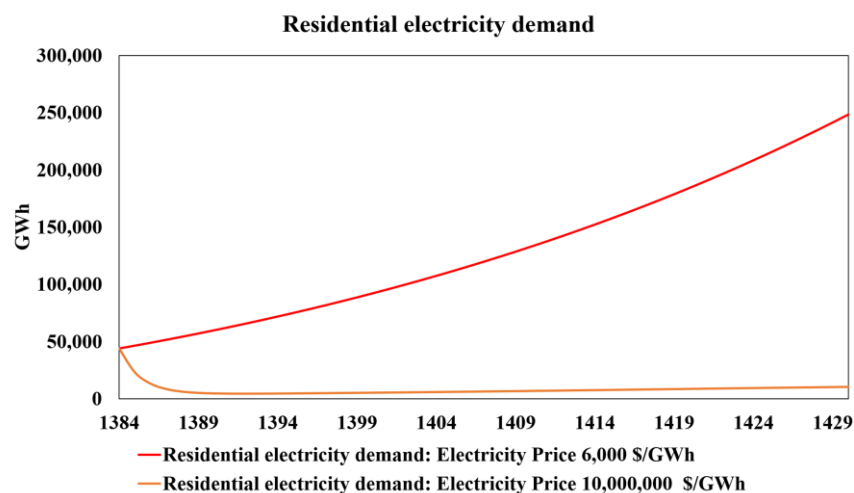


Figure 4. Extreme condition test- the impact of “Electricity Price” on “Residential Electricity Demand”

4.2. Dimensional consistency test

The dimensional consistency test ensures that all parameters in the model have appropriate units and that the units used across all equations are consistent. To evaluate the developed model, the unit check function in Vensim software was utilized. The findings confirm that the assigned units are fully consistent within the model (Stermann, 2000).

4.3. Validation: structurally oriented behavior test - behavior reproduction

The Behavior Reproduction Test is widely recognized as one of the most reliable methods for evaluating a model's performance. This test compares historical data with simulated results to validate the model's ability to replicate real-world behavior. While models inherently represent simplified versions of reality, their evaluation must consider both the structural logic of the model and the accuracy of the values it produces (Stermann, 2000).

For this study, historical data spanning the period from 1384 to 1403 (2005–2024) were used to validate the model. Seven key variables were assessed, and their behavioral trends are

illustrated in Figure 5. The diagrams demonstrate that the simulated results align closely with actual historical values, displaying consistent trends and indicating strong validity.

To complement the visual comparison, the Mean Absolute Percentage Error (MAPE) was calculated for all seven variables, yielding the following results:

1. Real Household Electricity Consumption per Capita: **3.36%**
2. Total Electricity Demand: **1.97%**
3. Thermal Power Plant Capacity: **8.76%**
4. Natural Gas Production Capacity: **5.81%**
5. GDP: **3.79%**
6. Population: **0.57%**

The low MAPE values for most variables confirm the favorable consistency between historical data and simulation outcomes. Although the capacity deficit exhibits a relatively higher error, this is due to its inherently dynamic and unpredictable nature. In conclusion, the high validity and accuracy of the model, as evidenced by the Behavior Reproduction Test and MAPE analysis, provide confidence in its ability to predict future trends based on the current system structure.

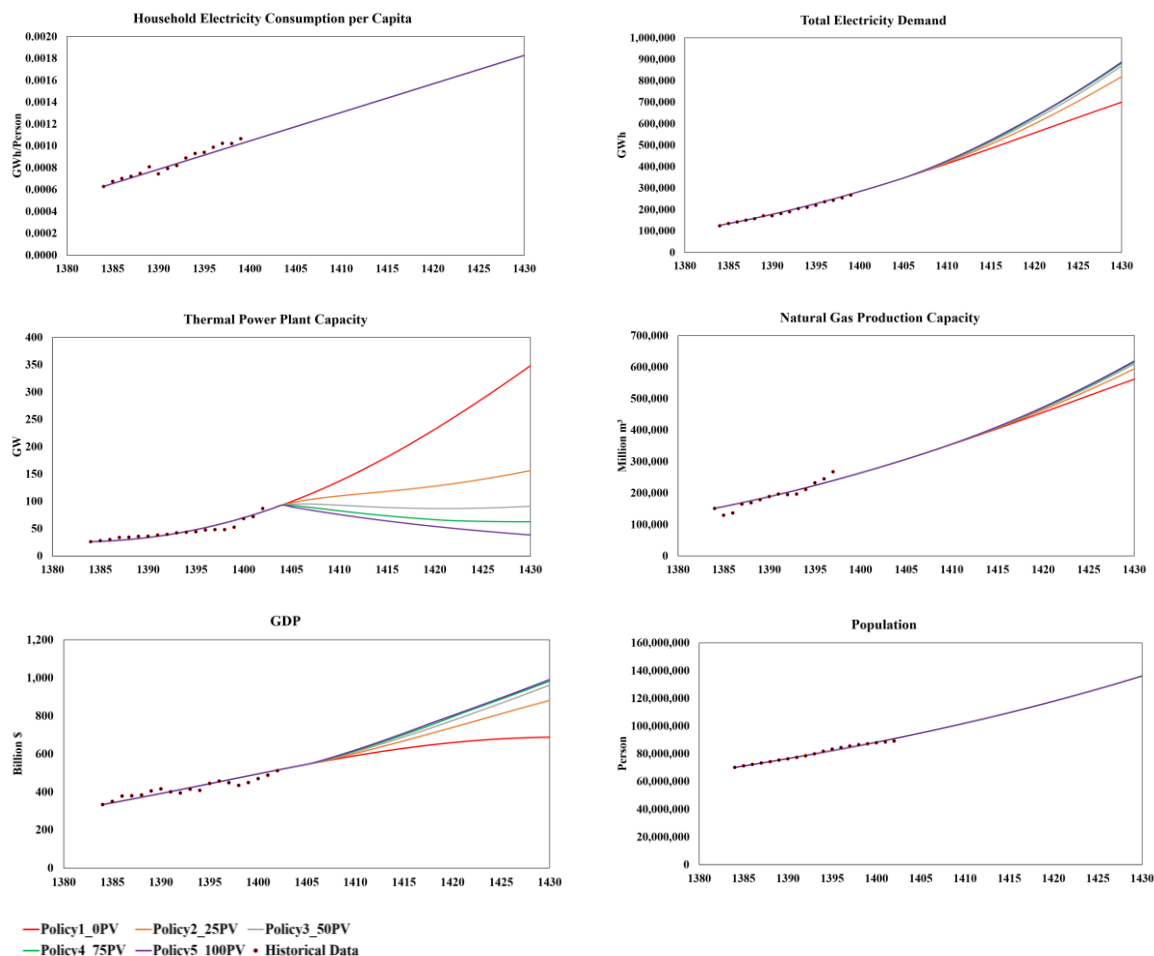


Figure 5. Structurally Oriented Behavior Test - Behavior Reproduction for the main variables of the model

4.4. Policy assessment and analysis

This section evaluates key variables for assessing various policy scenarios related to household PV development and their impacts on capacity deficit, electricity generation, water consumption, and emissions.

4.4.1. Electricity produced by PV

The implementation of policies promoting household PV development results in an increase in electricity generation from PV systems across all scenarios. As the power deficit grows due to rising total electricity demand, the financial investments required to address the deficit also increase. Consequently, a higher emphasis on household PV development leads to greater PV allocation. Accordingly, the projected electricity generation from PV systems in the year 1430 for policies 1 through 5 is as follows: 0, 246,875, 330,866, 457,612, and 589,250 GWh (Figure 6).

4.4.2. Power generation from thermal plants

Since the policies provide financial support for household PV systems, the budget allocated for the expansion of thermal power plants will be redirected towards household PV development. Consequently, the investment in thermal power plant expansion decreases in 1418 and 1421 under policies 5 and 4, respectively (Figure 6). However, under policies 2 and 3, both household PV systems and thermal power plants are developed simultaneously to address the power shortage, relying on government financial support.

4.4.3. Total power generation

Total power generation comprises the sum of electricity produced by thermal power plants and photovoltaic (PV) systems. This variable grows under all policies supporting household PV development. In 1404, total power generation was 215,469 GWh. By 1430, under policies 1 through 5, the increase is 405,661, 676,411, 771,188, 777,198, and 785,977 GWh, respectively (Figure 6). It indicates that without household PV expansion, total power generation grows by only 88.27%. However, with household PV development at 25%, 50%, 75%, and 100% levels, growth reaches 213.92%, 257.91%, 260.70%, and 264.77%, respectively, highlighting its effectiveness in addressing power deficits. The primary reasons for this substantial growth include the lower cost of household PV installations per unit of electricity produced, their higher efficiency, and shorter installation timelines compared to thermal power plants, enabling faster

and greater electricity generation under PV expansion policies.

4.4.4. *Capacity deficit*

The primary objective of this study is to analyze household PV expansion policies as a solution for addressing electricity deficits. As illustrated in Figure 5, the capacity deficit is projected to reach 43.3263 GW by 1430 if the government relies solely on developing thermal power plants. However, implementing household PV expansion policies significantly mitigates this power shortage, with reductions evident from the start of policy implementation in 1404.

By 1412, household PV policies can reduce the deficit to 12.9769, 7.86729, 5.59681, and 4.40932 GW under 25%, 50%, 75%, and 100% PV expansion scenarios, respectively. In contrast, relying exclusively on thermal power plant development results in a capacity deficit of 25.2102 GW. However, after 1416, nearly all PV expansion policies experience a gradual increase in capacity deficit, culminating by 1430 at 43.3263, 21.0619, 14.4305, 15.4442, and 14.94 GW for 0%, 25%, 50%, 75%, and 100% PV expansion scenarios, respectively. This increase is driven by rising electricity demand across residential, industrial, and service sectors.

This trend is reasonable because reducing the power deficit leads to GDP growth, which drives higher electricity demand in the production, service, and agricultural sectors. Higher GDP also raises per capita income, enabling greater electricity consumption. Additionally, GDP growth fosters increased investment in natural gas capacity expansion, boosting power generation from thermal power plants. However, this alone is insufficient to address the electricity deficit, necessitating complementary strategies, such as expanding household PV systems.

Over the long term, after 1421, policies 3, 4, and 5 (50%, 75%, and 100% PV expansion) outperform policies 1 and 2 (0% and 25% PV expansion) in reducing the capacity deficit. This demonstrates the effectiveness of household PV expansion as a critical measure for addressing power shortages and supporting sustainable energy planning.

4.4.5. *Total water consumption*

As illustrated in Figure 6, total water consumption in the power industry under Policy 5 (7,267,200 m³) begins to decline compared to Policy 1 (7,267,530 m³) in 1419, and under Policy 4 (9,294,160 m³) compared to Policy 1 (9,324,920 m³) in 1424. In both cases, the downward trend relative to Policy 1 continues steadily through 1430. However, the impact of household PV expansion on water consumption is not immediately apparent and becomes significant only

in the long term. This effect is most pronounced under the 75% and 100% PV expansion scenarios, resulting in reductions in water consumption of 3.03% and 11.51% relative to Policy 1, respectively. By 1430, water consumption is projected to be approximately 11,237,200, 11,383,500, 11,456,300, 10,897,100, and 9,943,260 million cubic meters for policies 1 through 5, respectively. These findings highlight the long-term benefits of household PV expansion in reducing water usage in the power sector, particularly under more ambitious deployment scenarios.

4.4.6. Emissions from power generation

As depicted in Figure 6, emissions from power generation under policy 5 (1463.67 Mt) begin to decline compared to Policy 1 (1463.75 Mt) in 1419. A similar trend is observed under Policy 4, where emissions (1877.29 Mt) fall below those of Policy 1 (1883.63 Mt) in 1424. This declining pattern relative to Policy 1 continues consistently up to 1430 for both Policy 4 and Policy 5. However, the impact of household PV expansion on emission reductions remains minimal until 1430, indicating a long-term effect. This impact is particularly pronounced under the 75% and 100% PV expansion scenarios, resulting in emissions reductions of 3.07% and 11.64%, respectively, compared to policy 1. By 1,430, emissions are projected to be approximately 2,275.52, 2,305.46, 2,320.34, 2,205.74, and 2,010.59 million tons of CO₂ equivalent for policies 1 through 5, respectively. These findings underscore the significant potential of extensive household PV expansion to mitigate emissions over the long term.

These findings highlight the significance of household PV expansion in addressing electricity deficits, optimizing resource consumption, and reducing environmental impacts.

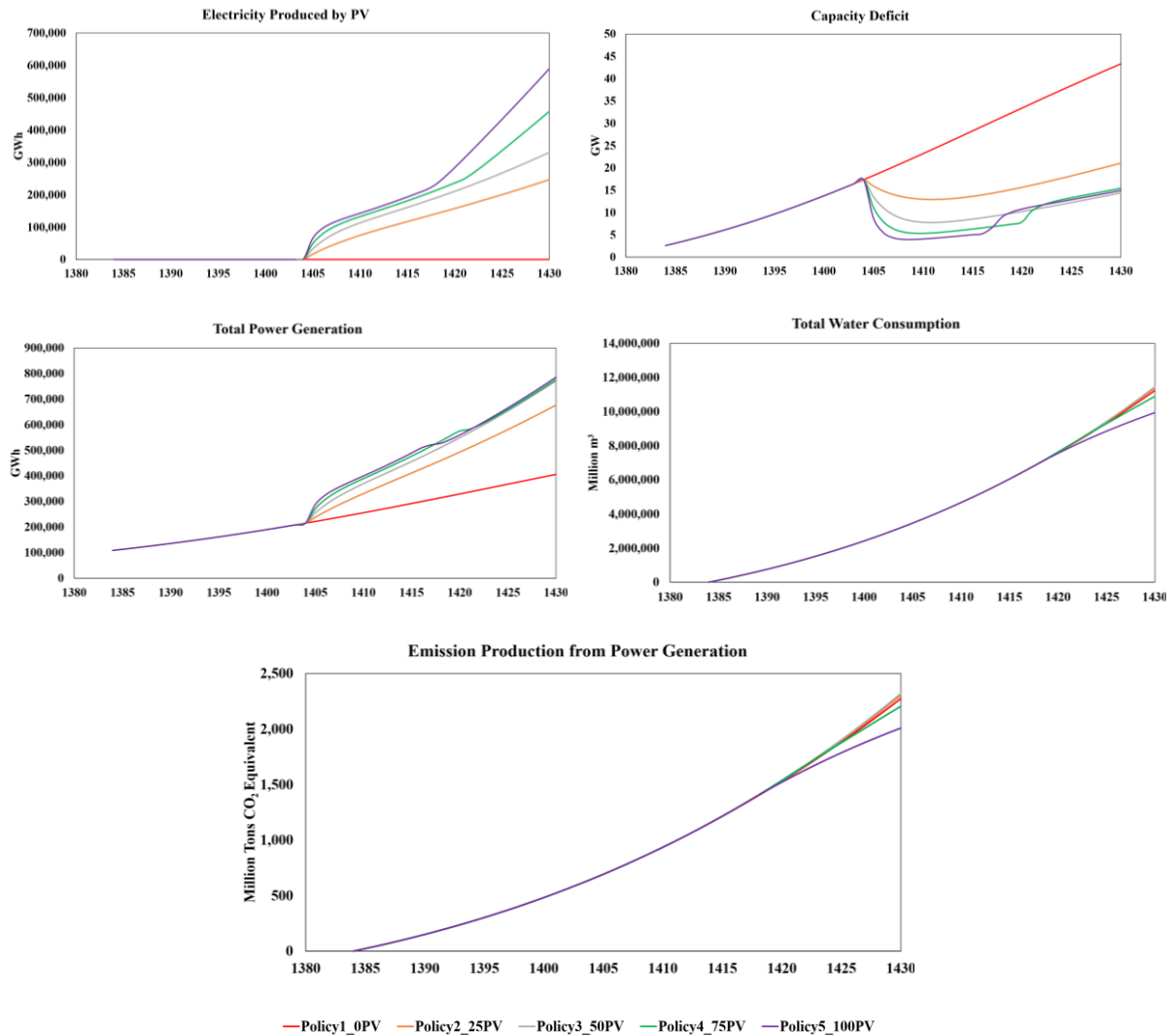


Figure 6. Trends of key variables for policy evaluation under various policy scenarios

5. Conclusion

This study assessed the effectiveness of household photovoltaic (PV) expansion policies in addressing Iran's electricity deficit, as well as their impact on CO₂ emissions and water consumption. The findings underscore the potential of household PV systems as a critical component of Iran's energy strategy, particularly in the short to mid-term. However, the results also reveal that household PV systems alone are insufficient to address the long-term power deficit, emphasizing the need for a comprehensive and diversified energy strategy. By employing a comprehensive system dynamic modeling approach with a low Mean Absolute Percentage Error (MAPE) of 1.97-8.76% across key variables, we provide a robust framework for informed policy recommendations that address critical gaps in the literature.

5.1. Key findings

- Our findings highlight the substantial potential of household PV systems in addressing electricity shortages through decentralized renewable solutions:
- **Significant PV generation capacity:** Household PV expansion policies can lead to electricity generation of up to 589,250 GWh by 1430 under the most ambitious scenario, underscoring the untapped potential of distributed solar energy in Iran.
- **Enhanced total power generation:** Expansion policies increase total power generation by 213.92% to 264.77% by 1430, compared to 88.27% growth under conventional thermal expansion alone, demonstrating the efficiency and feasibility of household PV systems.
- **Short-term deficit reduction:** PV expansion effectively mitigates the immediate electricity deficit, reducing it from 25.2102 GW in a thermal-only scenario to as low as 4.40932 GW under a 100% PV expansion policy by 1412.
- **Long-term deficit trends:** Despite short-term improvements, capacity deficits rise again after 1416 due to increasing demand, reaching 14.94-43.3263 GW by 1430, emphasizing the need for a holistic energy strategy.
- **Environmental benefits:** Ambitious PV deployment scenarios lead to CO₂ emission reductions of up to 11.64% and water savings of 11.51% by 1430, addressing Iran's water scarcity concerns while advancing sustainability objectives.

5.2. Contributions to energy policy and research

This study makes several critical contributions to energy policy planning and scientific literature:

- **Decentralized renewable strategy:** Unlike prior studies that focus on large-scale renewable projects, our research presents household PV as a direct and viable solution to electricity shortages, thereby bridging an important gap in the literature.
- **Optimal investment strategy:** We identify a 75% energy budget allocation for household PV as the most effective balance between deficit reduction, environmental benefits, and implementation feasibility, diverging from the broader renewable energy allocations in prior studies.
- **Comprehensive system dynamics framework:** Our model integrates supply-demand dynamics, technical constraints, and socio-economic factors, offering a holistic tool for evaluating household PV adoption and its impact on electricity deficits.
- **Temporal deficit analysis:** By assessing deficit trends across different timeframes, we demonstrate the necessity of complementary strategies beyond household PV for long-term sustainability.
- **Environmental-economic balance:** Our study quantifies the water and emissions savings associated with household PV adoption, providing a critical perspective on Iran's energy-water nexus.

5.3. Policy implications and future directions

The findings strongly support the adoption of Policy 4 (75% PV expansion) as the most balanced and effective strategy for Iran's electricity sector during the 1404-1430 (2025-2052) period. This approach provides multiple benefits:

1. **A 77.78% reduction in capacity deficit** by 1412 compared to thermal expansion alone.

2. **Environmental benefits**, including a 3.07% reduction in emissions and a 3.03% decrease in water consumption by 1430.
3. **Energy system stability**, by maintaining partial investment in thermal infrastructure while prioritizing household PV development.

Despite these advantages, additional measures will be required to address the projected long-term deficit of 15.4442 GW by 1430. Household PV systems should serve as a cornerstone of Iran's sustainable electricity strategy, but must be integrated with broader efforts, including efficiency improvements, grid modernization, and other renewable technologies.

Future research should explore complementary renewable sources, demand-side management, and advanced storage technologies to further enhance the resilience of Iran's energy system. Our validated system dynamics model provides a valuable tool for ongoing policy assessment and adaptation, ensuring a robust response to evolving energy challenges.

5.4. Limitations and suggestions

Despite its advantages, household PV systems alone cannot meet the long-term growing electricity demand. By 1430, even the most aggressive PV expansion scenarios reveal increasing capacity deficits driven by rising demand across residential, industrial, and service sectors. It underscores the urgency of adopting complementary strategies, including:

- **Investment in energy efficiency:** Enhancing energy efficiency across all sectors to curb electricity demand growth.
- **Diversification of renewable energy sources:** Expanding investments in wind, geothermal, and other renewable technologies to supplement PV systems.
- **Grid modernization:** Upgrading infrastructure to support decentralized generation and improved energy storage capabilities.
- **Demand-side management (DSM):** Implementing demand response programs and time-of-use pricing to optimize consumption patterns.
- **Natural gas utilization:** Allocating natural gas for export or as a transitional fuel in high-efficiency combined-cycle power plants to reduce emissions.

5.5. Limitations in broader applications

The proposed system dynamics model is designed specifically for Iran's electricity sector, and its direct application to other regions may require modifications due to differences in regulatory frameworks, economic conditions, and energy infrastructure. Key limitations include:

- **Financial and policy constraints:** The model assumes fixed financial investment scenarios and does not account for potential fluctuations in subsidies, tax incentives, or evolving regulatory policies that could impact PV adoption.

- **Storage and grid integration challenges:** The study does not explicitly model advancements in battery storage technologies or grid integration constraints, which could influence the feasibility of large-scale PV adoption in other contexts.
- **Regional variability:** Factors such as solar irradiance, land availability, and grid stability vary significantly across different regions, requiring localized assessments for effective implementation.
- **Socioeconomic considerations:** The model does not account for potential social acceptance challenges, behavioral factors, or economic inequalities that may influence household PV adoption in other markets.

Future research should address these limitations by incorporating dynamic policy models, exploring energy storage innovations, and analyzing broader socioeconomic impacts to refine the proposed strategies. By adopting a multifaceted approach that integrates household PV expansion with complementary measures, policymakers can effectively address Iran's electricity deficit, mitigate environmental impacts, and lay the groundwork for a sustainable and resilient energy future.

Disclosure statement

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References

- Alasseri, R., Tripathi, A., Rao, T.J. and Sreekanth, K.J., 2017. A review on implementation strategies for demand side management (DSM) in Kuwait through incentive-based demand response programs. *Renewable and Sustainable Energy Reviews*, 77, pp.617-635. <https://doi.org/10.1016/j.rser.2017.04.023>.
- Aryanpur, V., Atabaki, M.S., Marzband, M., Siano, P. and Ghayoumi, K., 2019. An overview of energy planning in Iran and transition pathways towards sustainable electricity supply sector. *Renewable and Sustainable Energy Reviews*, 112, pp.58-74. <https://doi.org/10.1016/j.rser.2019.05.047>.
- Asadi, M., Larki, I., Forootan, M.M., Ahmadi, R. and Farajollahi, M., 2023. Long-term scenario analysis of electricity supply and demand in Iran: Time series analysis, renewable electricity development, energy efficiency and conservation. *Sustainability*, 15(5), p.4618. <https://doi.org/10.3390/su15054618>.
- Audinet, Pierre; Rodriguez Pardina, Martin Augusto, 2010. *Managing an electricity shortfall : a guide for policymakers (English)*. Energy Sector Management Assistance Program (ESMAP) Washington, DC: World Bank. Available at: <http://documents.worldbank.org/curated/en/337601468017341236>.
- Balázs, I., Fodor, A. and Magyar, A., 2024. Short-term system imbalance forecast using linear and non-linear methods. *Energy Systems*, pp.1-22. <https://doi.org/10.1007/s12667-024-00667-7>.
- BarghNews, 2019. *Comparison of power grid loss percentage in Iran with other countries*. Available at: <https://barghnews.com/000AVe>. [in Persian].
- Ben Maalla, El Mehdi and Kunsch, P.L., 2008. Simulation of micro-CHP diffusion by means of system dynamics. *Energy Policy*, 36(7), pp.2308-2319. URL: <https://ideas.repec.org/a/eee/enepol/v36y2008i7p2308-2319.html>.

- Danso-Wiredu, E.Y., Dadson, Y.I. and Amoako-Andoh, F.O., 2016. Social, economic and environmental impacts of the recent electricity crisis in Ghana: A study of Winneba. *Journal of Social Sciences*, 49(3-1), pp.277-288. <https://doi.org/10.1080/09718923.2016.11893621>.
- Dehghan, H., Amin-Naseri, M.R. and Nahavandi, N., 2021. A system dynamics model to analyze future electricity supply and demand in Iran under alternative pricing policies. *Utilities Policy*, 69, p.101165. <https://doi.org/10.1016/j.jup.2020.101165>.
- Dehghan, H., Nahavandi, N., Chaharsooghi, S.K., Zarei, J. and Amin-Naseri, M.R., 2022. A hybrid game theory and system dynamics model to determine optimal electricity generation mix. *Computers & Chemical Engineering*, 166, p.107990. <https://doi.org/10.1016/j.compchemeng.2022.107990>.
- Doroodi, M., Ostadi, B., Kashan, A.H. and Zegordi, S.H., 2024. A hybrid method of system dynamics and design of experiments for investigating the economic and environmental indicators of electricity industry. *Heliyon*, 10(11). URL: [https://www.cell.com/heliyon/fulltext/S2405-8440\(24\)07291-8](https://www.cell.com/heliyon/fulltext/S2405-8440(24)07291-8).
- Energypress, 2024. *We are facing an 18,000 megawatt electricity imbalance/We do not want to say under what circumstances we took over the government*. Energypress. Available at: <https://energypress.ir/en/?p=2526>.
- Fasihizadeh, M., Sefti, M.V. and Torbati, H.M., 2014. Improving gas transmission networks operation using simulation algorithms: Case study of the National Iranian Gas Network. *Journal of natural gas science and engineering*, 20, pp.319-327. <https://doi.org/10.1016/j.jngse.2014.07.018>.
- Fisher-Vanden, K., Mansur, E.T. and Wang, Q.J., 2012. *Costly blackouts? Measuring productivity and environmental effects of electricity shortages* (No. w17741). National Bureau of Economic Research. URL: <https://www.nber.org/papers/w17741>.
- Foroutan, F., 2024. *Electricity price of thermal power plant*. Clean Energy. Available at: <https://clean-energy.ir/thermal-power-plant/>. [in Persian].
- Hoorayesh, 2021. *Steps to register and set up a home solar power plant*. Available at: <https://hoorayesh.com/bargh>. [in Persian].
- Hsu, C.W., 2012. Using a system dynamics model to assess the effects of capital subsidies and feed-in tariffs on solar PV installations. *Applied energy*, 100, pp.205-217. <https://doi.org/10.1016/j.apenergy.2012.02.039>.
- Kachoei, M.S., Salimi, M. and Amidpour, M., 2018. The long-term scenario and greenhouse gas effects cost-benefit analysis of Iran's electricity sector. *Energy*, 143, pp.585-596. <https://doi.org/10.1016/j.energy.2017.11.049>.
- Karbasioun, M., Gholamalipour, A., Safaie, N., Shirazizadeh, R. and Amidpour, M., 2023. Developing sustainable power systems by evaluating techno-economic, environmental, and social indicators from a system dynamics approach. *Utilities Policy*, 82, p.101566. <https://doi.org/10.1016/j.jup.2023.101566>.
- Khabaronline, 2011. Deputy Minister of Oil: Iran's Gas Will Last 156 More Years. Available at: <https://khabaronline.ir/x3dWq>. [in Persian].
- Khan, R.M., Farooq, S. and Gilal, M., 2020. A.(2020). Electricity Consumption and Economic Growth: A Time-Series Study on Pakistan. *Global Economics Review*, 1, pp.24-37. [http://dx.doi.org/10.31703/ger.2020\(V-I\).03](http://dx.doi.org/10.31703/ger.2020(V-I).03).

- Mahbub, T., 2023. *Encouraging Foreign Direct Investment (FDI) in Bangladesh's Power Sector*. pringerBriefs in Energy. Springer Nature Switzerland, Cham. <https://doi.org/10.1007/978-3-031-27990-4>.
- Masoomi, M., Panahi, M. and Samadi, R., 2022. Demand side management for electricity in Iran: cost and emission analysis using LEAP modeling framework. *Environment, Development and Sustainability*, 24(4), pp.5667-5693. <https://doi.org/10.1007/s10668-021-01676-7>.
- Mukhtar, M., Obiora, S., Yimen, N., Quixin, Z., Bamisile, O., Jidele, P. and Irvboje, Y.I., 2021. Effect of inadequate electrification on Nigeria's economic development and environmental sustainability. *Sustainability*, 13(4), p.2229. <https://doi.org/10.3390/su13042229>.
- News.Az, 2024. Iran's steel production drops sharply amid power shortages. News.Az. Available at: <https://news.az/news/irans-steel-production-drops-sharply-amid-power-shortages>
- Olausson, P.M., 2019. Planning for resilience in the case of power shortage: The Swedish STYREL policy. *Central European Journal of Public Policy*, 13(1), pp.12-22. <https://doi.org/10.2478/cejpp-2019-0004>.
- Pazheri, F.R., Othman, M.F., Malik, N.H. and Safoora, O.K., 2012. Economic and environmental dispatch at highly potential renewable area with renewable storage. *International Journal of Environmental Science and Development*, 3(2), pp.177-182.
- Roybal, L.G. and Jeffers, R.F., 2013. *Using system dynamics to define, study, and implement smart control strategies on the electric power grid* (No. INL/CON-13-28641). Idaho National Lab.(INL), Idaho Falls, ID (United States). URL: <https://www.osti.gov/biblio/1097180>.
- Safari Dehkordi, F., 2024. One-third of the country's gas allocated to power plants. Mehr News Agency. Available at: <https://mehrnews.com/x36n3g>. [in Persian].
- Shana, 2025. Power plants set new gas consumption record: 312 million cubic meters in one day. Shana. Available at: <https://www.shana.ir/news/662545>. [in Persian].
- Shokri, U., 2024. *Powering change: Iran's electricity crisis and the path forward under Pezeshkian*. bne IntelliNews. Available at: <https://www.intellinews.com/powering-change-iran-s-electricity-crisis-and-the-path-forward-under-pezeshkian-333922/>
- Sterman, J.D., 2000. *Business Dynamics: Systems thinking and modeling for a complex world*. MacGraw-Hill Company.
- Techsunsanat, n.d. How much does it cost to set up and install a home solar panel? Available at: <https://techsunsanat.ir/blog/howmuch-does-it-cost-to-setup-and-install-a-home-solar-panel/> [in Persian].
- Tehran Times, 2024. Electricity consumption in Iran rises 6,000 MW. Tehran Times. Available at: <https://www.tehrantimes.com/news/502153/Electricity-consumption-in-Iran-rises-6-000-MW>. [in Persian].
- Tofigh, A.A. and Abedian, M., 2016. Analysis of energy status in Iran for designing sustainable energy roadmap. *Renewable and Sustainable Energy Reviews*, 57, pp.1296-1306. <https://doi.org/10.1016/j.rser.2015.12.209>.
- Usman, M. and Jie, Z., 2022. Power shortages in Pakistan Causes and Solutions: Power shortages in Pakistan Causes and Solutions. *Journal of Social Sciences and Economics*, 1(1), pp.24-29. <http://dx.doi.org/10.61363/jsse.v1i1.38>.

- Vasconcelos, P.N., de Souza, A.Z., Ribeiro, P.F. and Balestrassi, P.P., 2021, April. Modeling the Power Sector of Wonderland: an integrated system dynamics model to assess a sustainable regional development. In *2021 IEEE Mexican Humanitarian Technology Conference (MHTC)* (pp. 38-45). IEEE. . <https://doi.org/10.1109/MHTC52069.2021.9419950>.
- Zhang, F., 2018. *In the dark: how much do power sector distortions cost south Asia?*. World Bank Publications.
- Zhang, W., Ji, C., Liu, Y., Hao, Y., Song, Y., Cao, Y. and Qi, H., 2024. Dynamic interactions of carbon trading, green certificate trading, and electricity markets: Insights from system dynamics modeling. *PLoS One*, 19(6), p.e0304478. <https://doi.org/10.1371/journal.pone.0304478>.

Designing an Optimal Control Model of a Capacity, Multi-stage Continuous MRP System Considering Delay in Production Lead Time and the Possibility of Reworking and Recycling

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ABSTRACT

In this paper, we propose a multi-stage continuous-MRP system using an optimal control model, considering the production lead time. In the proposed model, the lead time is specified for ordering work in process during the second stage and for final product manufacturing. Also, the intended dynamical system is a multi-stage production-inventory system that follows a linear-quadratic optimal control model with a time delay for the state variables. In the proposed system, inventories are considered state variables, and the delivery levels and orders are control variables. The return stage is considered for items whose production has been defective. According to their situation, there are three destinations: the reworking stage, the recycling stage, or disposal. The amount of shipment to the next stage of production is based on their BOM utilization coefficient and the inventory one. This stage will consume all sent items at any time and will not create a surplus inventory. In this paper, time is considered a continuous parameter proportional to the constant production processes. For validation, the proposed optimal control model was simulated in a real study in the polymer industry.

Keywords

Optimal control, Continuous material requirements planning (CMRP), Deteriorating items, Lead Time, Reworking, Recycling.

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1. Introduction

Maintaining an inventory of raw materials incurs significant costs for manufacturing companies, particularly in the mass production industry, prompting managers to consider more carefully how to find the optimal solution to this problem. The primary achievement of a required material planning system is the planning of part and goods production, as well as the supply of raw materials, to ensure the production line can meet the required quantities at the necessary time. Proper scheduling of raw materials purchases, on the one hand, and timely ordering of parts for production, on the other, will lead to more reliable access to the raw materials needed on the production line and the timely delivery of products according to a comprehensive production schedule. If material requirements planning is successfully implemented, overall inventory costs will be significantly reduced. Most studies on finite- or infinite-capacity MRP systems focus on discrete-time systems. However, precise material requirements planning is required at a consistent time. Discrete materials requirements planning (DMRP) approach defines orders, demands, and products at a discrete time or Specific periods. Therefore, the discreteness in the DMRP approach implies a breakdown in production time. In this approach, the production parameters are defined over a fixed time. Thus, the available inventory is determined from the beginning of the period.

In contrast, in Continuous Material Requirement Planning (CMRP) systems, the production parameters are determined at each moment of the planning time horizon. In some industries, such systems need to be considered because of their continuous production. In the petrochemical and petroleum industries, for example, production occurs continuously, and inventory levels are constantly changing. However, most of the research become established. On the other hand, in the last decade, the use of optimal control theory in production planning and inventory control has increased. Therefore, the literature on MRP and the application of optimal control theory in production inventory systems are discussed for better understanding.

[Sadeghian \(2011\)](#) first introduced the CMRP approach and subsequently discussed its advantages over the DMRP. He then presented a three-step algorithmic method for determining scheduled orders in discrete MRP. In this algorithm, the scheduled orders were calculated without an optimization approach. [Louly et al. \(2012\)](#) attempted to plan components in assembly systems using the MRP approach. In their proposed model, the lead time was randomly selected. [Grubbstrom and Tang \(2012\)](#) examined the effect of demand scheduling and BOM conditions on the Solution space for production times. [Milne et al. \(2015\)](#) developed

a mixed-integer programming approach to determine the optimal lead time for use in MRP systems for discrete component production and a fixed-period batch size policy. [Rossi et al. \(2017\)](#) suggested a capacity compatible with the MRP model. In their proposed model, finite capacity was taken into account. They also determined a fixed lead time.

[Le Thi and Tran \(2014\)](#) discussed a plan to optimize the costs of setting up, transporting, and inventing a multistage production system. Their optimization model was a nonlinear, complex integer programming model. [Mezghiche et al. \(2015\)](#) considered an integrated production forecasting system of tracking type. In their proposed system, the demand rate over a given period depends on the demand rate of the previous period and the stock level. [Hatami-Marbini et al. \(2020\)](#) considered a network of manufacturing machines based on the hedging point policy where the final goods were perishable, and the demand rate was constant. [Lee et al. \(2021\)](#) proposed a double-ended queuing model having backorders and customer abandonment. One side of their model stores back orders, and the other side represents inventory.

[Foul et al. \(2012\)](#) presented an adaptive inventory system with an unknown deterioration rate. [Vercraene and Gayon \(2013\)](#) focused on the optimal control model of a production inventory system with disposable items and product returns. [Pooya and Pakdaman \(2021\)](#) presented a manpower planning problem from a continuous-time optimal control. [Dhaiban \(2022\)](#) proposed a new approach to finding integer solutions for the product inventory control model under a periodic review policy. Their approach was based on the modified equations of the Pontryagin maximum principle. [Singer and Khmelnitsky \(2021\)](#) considered a stochastic production-inventory problem and solved it using optimal control methods. [ElHafsi et al. \(2021\)](#) addressed the problems faced by manufacturers in dealing with customers with diverse needs and determining which customers to serve when supply is limited, within a continuous-time integrated manufacturing and inventory control framework. [Gao \(2022\)](#) extended the production-inventory model with a stochastic term, and instead of analyzing steady states or guessing the shape of the solution, they focused on PDEs. She applied the operator division method after the Cole-Hopf transformation to the initial equation, rather than solving the ODE system. [Shen et al. \(2022\)](#) investigated the uncertain production-inventory problem with deteriorating items and developed an optimal control model in their research. They applied uncertainty theory to derive the optimal equation. [Nakhaeinejad et al. \(2023\)](#) used the optimal control theory to propose an order system and inventory management model. In their model, the order was regarded as a time-dependent function and a control variable. In addition, the need for each item was time-dependent and specified. The order and inventory system was indicated as an optimal control problem.

Hedjar et al. (2012) employed optimal control theory to determine the optimal production rates in a production system. Mezghiche et al. (2015) presented a unified production forecasting system using the control approach. In their proposed system, the demand rate over a given period depends on the demand rate of the previous period, and the stock level. Benkherouf et al. (2016) proposed an optimal control model for production and reworking in the inventory system with finite planning horizons. Dizbin and Tan (2020) considered the production control problem of a production-inventory system with correlated demand, inter-arrival, and processing times. They proved that the optimal control policy is the state-dependent threshold policy. Al-Khazraji et al. (2021) scrutinized the dynamic performance of the APIOBPCS model and the newly modified 2APIOBPCS model for optimal control of production–inventory systems in their study. Öztürk (2021) investigated an economic production quantity model that explored the impacts of a flawed manufacturing process with stochastic breakdowns and inspection policies on a manufacturing inventory system with a repair, and determined the optimal production run time.

Pooya and Pakdaman (2017) proposed an optimal control model for production-inventory models. They solved the proposed optimal control problem with a neural network approach. In most models discussed in the production field, it is assumed that production occurs in a single stage. They also (2018) proposed a delayed optimal control model for a multi-stage production-inventory system with production lead times. Still, their planning approach was not MRP and merely managed the inventory of the various stages. In another article (2019), they proposed an optimal control model for finite capacity continuous MRP, which does not consider production lead time, including returned, reworked, and recycled goods with deteriorating items. Rachih et al. (2022) addressed a discrete inventory control model for a reverse logistics system in their paper. In their work, the optimal control policy consisted of minimal levels for stocks of returns and new products and higher levels for remanufactured products. In contrast, the demand for new products was higher than the demand for remanufactured products. Ignaciuk (2022) examined the perspectives of linear-quadratic (LQ) optimal control in steering the process of goods distribution in logistic systems with multiple transportation options. Megoze et al., (2022) presented a study on a manufacturing and remanufacturing system that degrades according to its production rate. After formulating the optimal control problem that described the studied system, they solved the HJB equations using a numerical method.

In many cases, production phasing and planning for each stage separately may be more desirable. Primarily, when using equipment and machinery in separate, sequential applications,

it is very cost-effective because it allows for flexibility in planning and reduces production costs with a more accurate schedule. However, multi-stage production systems still occur despite the production lead time, which neglect leads to incorrect planning and either increasing or decreasing inventory. On the other hand, considering that in such production systems, there is a possibility of defective goods after each stage, it is necessary to consider the return stage to rework the returned product or recycle it into the raw materials of the previous step.

Table 1 provides a summary of the research conducted in the field of the present study. The earlier models each had deficiencies in the multi-stage continuous MRP system, considering the finite capacity, the delay in production lead time, and the possibility of re-working and recycling. Many of the previous papers have proposed discrete-time models.

[Grubbstrom et al. \(2010\)](#) considered no capacity constraints. [Ignaciuk and Bartoszewicz \(2010\)](#) dismiss the disposal phase of deteriorating items. [Sadeghian \(2011\)](#) presented a continuous MRP model paper with no optimization approach. [Louly et al. \(2012\)](#) regarded lead time as a random variable. [Vercraene and Gayon \(2013\)](#) presented a two-stage model that ignored recycling. The proposed models did not apply to production systems, despite the industries' production nature being continuous, such as the petroleum and petrochemical industries, as well as some of the products in the construction industry. [Benkherouf et al. \(2016\)](#) presented a model that lacked a recycling stage. [Pooya and Pakdaman \(2018\)](#) did not consider the process of disposing of deteriorating items and reworking. In another paper [\(2019\)](#), they presented a model in which production LTs were considered as zero. [Al-Khazraji et al. \(2021\)](#) presented a continuous optimal control model that considered production lead time but did not account for the return, rework, and recycling stages. [Öztürk \(2021\)](#) proposed a delayed optimal control model with a reworking stage, but in the proposed model, the stages of recycling and disposal of perishable items were neglected. [ElHafsi et al. \(2021\)](#) and [Gao \(2022\)](#) proposed continuous models that do not account for production lead time. In their models, they dismiss the stage of disposal of deteriorating items. [Shen et al. \(2022\)](#) and [Megoze et al., \(2022\)](#) investigated the production-inventory problem with deteriorating items, where the production LTs were considered zero. [Rachih et al. \(2022\)](#) addressed a discrete inventory control model in their paper. Although they included the rework stage in the model, the production lead time was ignored. The challenge observed in earlier models is the lack of a comprehensive model to be proposed for a multi-stage continuous MRP system with finite capacity, considering production LTs with deteriorating items.

[Yan and Sun \(2024\)](#) employ constrained reinforcement learning to solve an optimal control problem aimed at reducing fuel consumption in hybrid energy systems. By accounting for

uncertainty and fluctuations in input data (such as sensor errors or changes in environmental conditions) and integrating prediction with dynamic decision-making, they propose a multi-stage framework that can be adapted to MRP systems with rework and recycling capabilities. [Luo et al. \(2024\)](#) focus on a model predictive control (MPC) approach to optimize computations in the presence of input delays. By predicting future states and solving the optimal control problem one step ahead, they significantly reduce delays in implementing controls.

In this study, we introduce an optimal control multi-stage continuous MRP system with finite capacity, considering production LTs with deteriorating items. Purchase and manufacturing orders, shipments, and quantities returned from the market were considered control variables, while inventories were treated as system states. Production LTs are to be the time required for the production and purchase orders. In the proposed multi-stage system, it is permissible to move the returned items from one inventory to the previous one due to the recycling and reworking stages. An essential advantage of the proposed model, which was not addressed in previous models, is that the number of items sent to the next stage must be a coefficient of their use in the BOM as well as a coefficient of inventory. In other words, the number of goods shipped at any given moment in time should be large enough to be used in production at all times and not lead to a surplus inventory of any item at a later stage. The bottom line of Table 1 shows the features of the present study. There are two main steps to be solved by the theory of optimal control: the modelling stage, or model description, and the model solving stage.

The first section of this study is (Model Descriptions) devoted to modelling and model description. In this section, the proposed model and related diagrams are presented. Also, two mathematical models for the delay and non-delay modes are offered. In the second section (Model solving), the proposed linear-quadratic optimal control model is analyzed and solved. In the third section (numerical simulation), the proposed model is solved using the actual parameters studied. The fourth section (Sensitivity Analysis for Q , K and R) is devoted to evaluating the proposed model. Finally, the last section (Discussion and Conclusion) includes a discussion of model features, conclusions, and future research suggestions.

Table 1. Previous research on MRP mathematical models and challenges

Author	Topic	Type of Model	Model Challenge						
			Discrete Time	No possibility of reworking	One-stage	Without LT	Infinite capacity	No possibility of recycling	No optimization BOM is not allowed
Sadeghian (2011)	MRP	MRP							*
Grubbstrom et al. (2010)	MRP	MRP	*				*		
Rossi et al. (2017)	MRP	MRP	*						
Milne et al. (2015)	MRP	MRP	*						
Louly et al. (2012)	MRP	MRP	*						
Grubbstrom and Tang (2012)	MRP	MRP	*						
Le Thi and Tran (2014)	MRP	Integer nonlinear programming model	*						
Hedjar et al. (2012)	Optimal control applications in production planning and inventory control	Continuous optimal control						*	
Dizbin and Tan (2020)		Continuous optimal control		*				*	* *
Mezghiche et al. (2015)	"	Continuous optimal control		*				*	
Pooya and Pakdaman (2017)	"	Continuous optimal control		*		*		*	*
Pooya and Pakdaman (2018)	"	Continuous optimal control		*				*	
Pooya et al. (2019)	"	Continuous optimal control			*				*
Pooya and Pakdaman (2019)	"	Continuous optimal control				*			
Singer and Khmelnitsky (2021)		Continuous optimal control		*		*		*	*
Dhaiban (2022)		Continuous optimal control		*		*	*	*	*
Dong et al. (2011)	"	Continuous optimal control, multi-stage							*
Hatami-Marbini et al. (2020)		Continuous optimal control				*		*	*
Benkherouf et al. (2016)	"	Continuous optimal control		*				*	
Vercraene and Gayon (2013)	"	Discrete optimal control, two-stage	*					*	*
Lee et al. (2021)		Continuous optimal control		*		*		*	*
Ignaciuk and Bartoszewicz (2010)	"	Discrete optimal control, multi-stage	*						*
Al-Khazraji et al. (2021)	"	Continuous optimal control							*

Author	Topic	Type of Model	Model Challenge						
			Discrete Time	No possibility of reworking	One-stage	Without LT	Infinite capacity	No possibility of recycling	No optimization BOM is not allowed
Öztürk (2021)	"	Continuous optimal control		*		*		*	*
ElHafsi et al. (2021)	"	Continuous optimal control				*		*	*
Gao (2022)	"	Continuous optimal control				*		*	*
Shen et al. (2022)	"	Continuous optimal control				*		*	*
Rachih et al. (2022)	"	Discrete optimal control	*	*		*			*
Megoze et al. (2022)	"	Continuous optimal control		*		*		*	*
Ignaciuk (2022)	"	Discrete optimal control	*			*		*	*
Yan and Sun (2024)	MRP: Optimal control applications in production planning and inventory control	Continuous optimal control, multi-stage, stochastic	*			*	*		*
Luo et al., 2024	Optimal control applications in production planning and inventory control	Continuous optimal control, multi-stage	*	*			*	*	*
present study	"	Continuous optimal control, multi-stage	Continuous	possibility of reworking	multi-stage	Existence of LT	Finite capacity	possibility of recycling	Optimization Existence of BOM

2. Model descriptions

The proposed model in this study will be a multi-stage production-inventory planning model that involves returning, recycling, and reworking the returned products. Since the proposed model will consider the production lead time in each stage, two models are presented. In the first model, the production lead time will be zero, and in the second model, the actual lead time will be considered at each stage of production. The intended production-inventory system produces a final product called A . In the first stage of the model, two raw materials (b and c) will be bought and assembled. Then, the work in process (A_1) will be produced. In the second stage, the work in process will be mixed with the raw material (d), and the final item (A) will be produced. To produce each unit of (A_1), we need α unit of b and β unit of c . In the next stage, to make each unit of A , we need δ unit of A_1 and γ unit of d (figure 1).

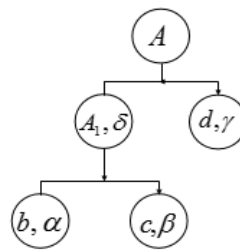


Figure 1. product three-level tree

Pooya and Pakdaman (2019) presented an MRP optimal control model for finite capacity without considering the lead time. In another article (2018), they offered a multi-stage model considering production lead time. The proposed model in this study combines these two models. The multi-stage production-inventory system shown in Figure 2 is a continuous MRP model, including the stages of recycling and reworking on returned items. In this model, the disposal stage of deteriorating items is also considered. In the proposed model above, the first step is ordering the raw materials (b and c), which is shown with $s_{mb}(t)$ and $s_{mc}(t)$, respectively. The amount of these two raw materials in the unit of time also equals to $I_{mb}(t)$ and $I_{mc}(t)$. Next, by combining the two raw materials, the work in process (A_1) is produced. The amount of shipment of the above items for production equals to $P_{mb}(t)$ and $P_{mc}(t)$, respectively. The first stage inventory ($I_{mA_1}(t)$) will be divided into two parts. Part of the inventory will be sent to the next stage ($P_{mA_1}(t)$) for A production and the other part will be returned at a ω_{m1} rate. Some of the returned goods will be shipped to the remanufacturing or reworking stage at a ω_{RA_1} rate and some will be referred to the recycling stage at a ω_{CA_1} rate (from the inventory of recycled goods, the part related to the raw material b ($C_{rb}(t)$) will be added to the inventory of b and part related to the raw material (c) will be added to the inventory of c).

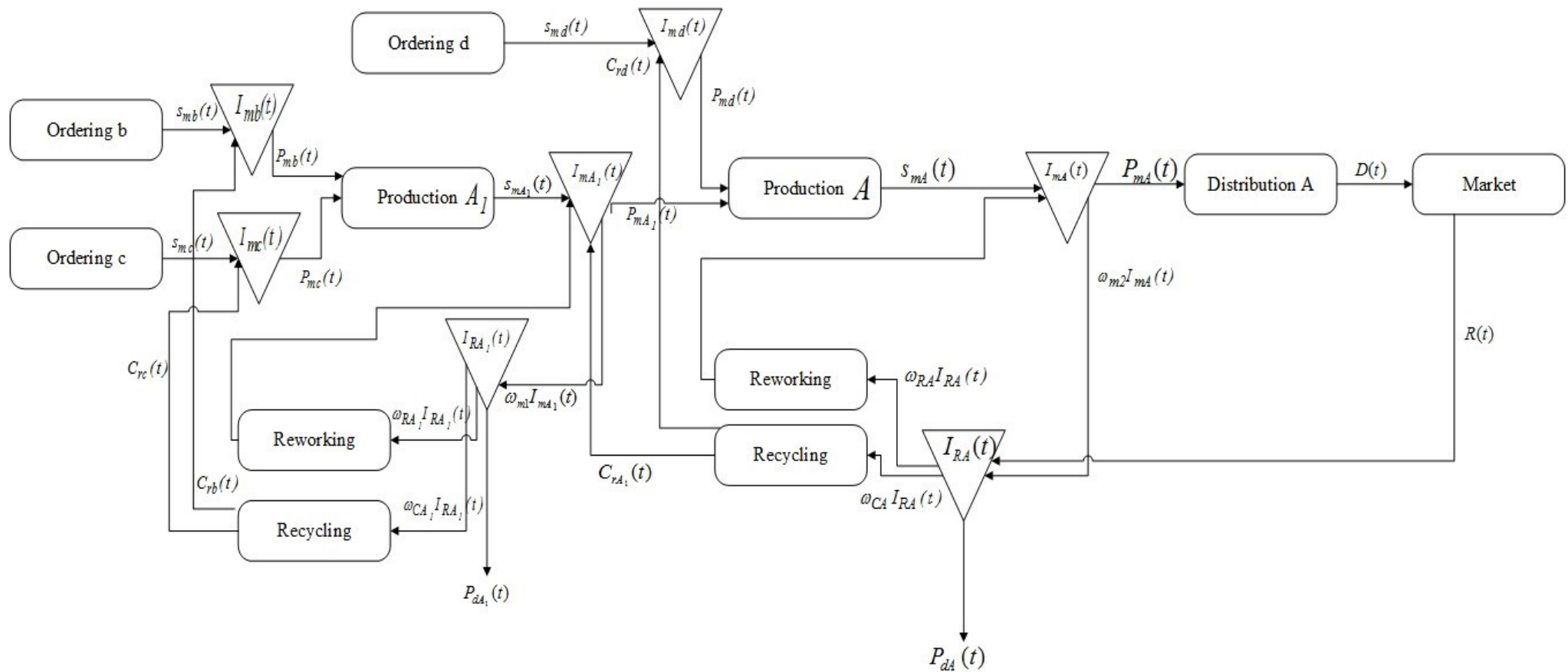


Figure 2. Diagram of the proposed model

The remaining items at this stage that cannot be reworked or recycled will be disposed of at a ω_{dA_1} rate. In the second stage of production, the inventory of manufactured goods ($I_{mA}(t)$) will be divided into two parts. Part of the inventory will be shipped to the market based on the market demand ($D(t)$) (that $P_{mA}(t) = D(t)$) and the remainder will constitute returned goods at the rate (ω_{RA}) and returned goods, similar to the preceding two-stage, will be added to the remanufacturing (ω_{dA}) or recycling stage (at the rate ω_{CA}) and some of them will be disposed of at the ω_{dA} rate. Some of the shipped goods will also be returned to the market ($R(t)$) which will be added to the second stage returned goods inventory.

The variables and parameters used in the model will be as follows. These symbols are used throughout the article for state and control variables.

State and control variables

$I_{mb}(t)$: Inventory of ordered items b at time t
 $I_{mc}(t)$: Inventory of ordered items c at time t
 $I_{md}(t)$: Inventory of ordered items d at time t
 $I_{mA_1}(t)$: Inventory of ordered items A_1 at time t
 $I_{mA}(t)$: Inventory of manufactured final production A at time t
 $I_{RA_1}(t)$: Inventory of returned items A_1 at time t
 $I_{RA}(t)$: Inventory of returned final production A at time t

Control variables

$s_{mb}(t)$: Level of ordering and releasing the items b at time t
 $s_{mc}(t)$: Level of ordering and releasing the items c at time t
 $s_{md}(t)$: Level of ordering and releasing the items d at time t
 $s_{mA_1}(t)$: Level of ordering and releasing the WIP items A_1 at time t
 $s_{mA}(t)$: Level of ordering and releasing the final production A at time t
 $P_{mb}(t)$: Level of items b which will be transmitted for producing A_1 at time t
 $P_{mc}(t)$: Level of items c which will be transmitted for producing A_1 at time t
 $P_{md}(t)$: Level of items d which will be transmitted for producing A at time t
 $P_{mA_1}(t)$: Level of WIP items A_1 which will be transmitted for producing A at time t
 $P_{mA}(t)$: Level of manufactured and released items A at time t
 $C_{rb}(t)$: Level of recycled items b at time t
 $C_{rc}(t)$: Level of recycled items c at time t
 $C_{rd}(t)$: Level of recycled items d at time t
 $C_{rA_1}(t)$: Level of recycled WIP items A_1 at time t
 $D(t)$: Released demand of manufactured items A at time t
 $R(t)$: Level of returned items A from market at time t

Parameters

ω_{m1} : Rate of returning in the stock of manufactured WIP items A_1
 ω_{m2} : Rate of returning in the stock of manufactured final production A
 ω_{RA_1} : Rate of reworking in the stock of returned WIP items A_1

ω_{RA} : Rate of reworking in the stock of returned final production A
 ω_{CA_1} : Rate of recycling in the stock of returned WIP items A_1
 ω_{CA} : Rate of recycling in the stock of returned final production A
 ω_{dA_1} : Deterioration rate in the stock of reworked WIP items A_1
 ω_{dA} : Deterioration rate in the stock of reworked final production A
 α : Number of items b which will be used for producing A_1
 β : Number of items c which will be used for producing A_1
 γ : Number of items d which will be used for producing A
 δ : Number of item A_1 which will be used for producing A
 τ_{A_1} : Production Lead Time for WIP items A_1
 τ_A : Production Lead Time for final production A

The number of shipped items (b and c) should be a coefficient of their use in the BOM as otherwise, the amount of raw material shipped for production A_1 would be excessive. This coefficient is defined a . In other words, the number of goods shipped at any time should be such that they are all used for production A_1 and there is no additional shipment of any of them. It should also be a coefficient on the amount of inventory available at any given time. So, it can be stated:

$$\begin{cases} P_{mb}(t) = a\alpha I_{mb}(t) \\ P_{mc}(t) = a\beta I_{mc}(t) \end{cases} \quad (1)$$

But given that the number of items shipped at any time should be less than the number of goods above, so it should be $0 < a\alpha, a\beta \leq 1$.

The order of manufactured item (A_1) at any given time is obtained from the following relationship:

$$s_{mA_1}(t) = \min \left\{ \frac{P_{mb}(t)}{\alpha}, \frac{P_{mc}(t)}{\beta} \right\} \quad (2)$$

In order not to ship items b and c in production A_1 more than the production need, it should be:

$$\frac{P_{mb}(t)}{\alpha} = \frac{P_{mc}(t)}{\beta} \quad (3)$$

So it can be stated:

$$s_{mA_1}(t) \min \left\{ \frac{P_{mb}(t)}{\alpha}, \frac{P_{mc}(t)}{\beta} \right\} = \frac{P_{mb}(t)}{\alpha} = \frac{P_{mc}(t)}{\beta} \quad (4)$$

According to the relationships (1):

$$\begin{cases} P_{mb}(t) = a\alpha I_{mb}(t) \Rightarrow \frac{P_{mb}(t)}{\alpha} = aI_{mb}(t) \\ P_{mc}(t) = a\beta I_{mc}(t) \Rightarrow \frac{P_{mc}(t)}{\beta} = aI_{mc}(t) \end{cases} \quad (5)$$

According to the relationship (3):

$$aI_{mb}(t) = aI_{mc}(t) \Rightarrow I_{mb}(t) = I_{mc}(t) \quad (6)$$

In the next stage, the manufactured product will be transformed into the final product (A) by mixing the raw material (d). At this point, the shipping rate of the above items is equal to $P_{md}(t)$ and $P_{mA_1}(t)$, respectively. Similar to the one described in the previous stage, we can conclude the following relationships (here the coefficient $\hat{b}$ is defined):

$$\begin{aligned} P_{md}(t) &= \hat{b}\gamma I_{md}(t) \\ P_{mA_1}(t) &= \hat{b}\delta I_{mA_1}(t) \end{aligned} \quad (7)$$

In which $0 < \hat{b}\gamma, \hat{b}\delta \leq 1$.

At this point, the manufactured product order A must follow the following relationship at all times.

$$s_{mA}(t) = \min \frac{P_{md}(t)}{\gamma}, \frac{P_{mA_1}(t)}{\delta} \quad (8)$$

In order not to ship items d and A_1 in production A more than the production need, it should be:

$$\frac{P_{md}(t)}{\gamma} = \frac{P_{mA_1}(t)}{\delta} \quad (9)$$

And according to the relationships (9) and similar to the above, it can be stated:

$$I_{mA_1}(t) = I_{md}(t)$$

By placing relationships (3) and (9) in relationships (2) and (8), the following relationships will be achieved:

$$\begin{cases} s_{mA_1}(t) = \min \left\{ \frac{P_{mb}(t)}{\alpha}, \frac{P_{mc}(t)}{\beta} \right\} = \frac{P_{mb}(t)}{\alpha} = \frac{P_{mc}(t)}{\beta} = \frac{1}{2\alpha} P_{mb}(t) + \frac{1}{2\beta} P_{mc}(t) \\ s_{mA}(t) = \min \left\{ \frac{P_{md}(t)}{\gamma}, \frac{P_{mA_1}(t)}{\delta} \right\} = \frac{P_{md}(t)}{\gamma} = \frac{P_{mA_1}(t)}{\delta} = \frac{1}{2\gamma} P_{mb}(t) + \frac{1}{2\gamma} P_{mA_1}(t) \end{cases} \quad (10)$$

And according to Figure 2, and recycling and detritation rates it can be stated:

$$\begin{cases} C_{rb}(t) = \omega_{CA_1} I_{RA_1}(t) \\ C_{rc}(t) = \beta \omega_{CA_1} I_{RA_1}(t) \\ C_{rd}(t) = \gamma \omega_{CA_2} I_{RA}(t) \\ C_{rA_1}(t) = \delta \omega_{CA_2} I_{RA}(t) \end{cases} \quad (11)$$

$$\begin{cases} P_{dA_1}(t) = \omega_{dA_1} I_{RA_1}(t) \\ P_{dA}(t) = \omega_{dA} I_{RA}(t) \end{cases}$$

2.1. Model one: The mode without considering the lead time

The dynamic behavior of the above-proposed model can be expressed in terms of the following relationships:

$$\begin{cases} \dot{I}_{mb}(t) = s_{mb}(t) + C_{rb}(t) - P_{mb}(t) & I_{mb}(0) = I_{mb}^0 \\ \dot{I}_{mc}(t) = s_{mc}(t) + C_{rc}(t) - P_{mc}(t) & I_{mc}(0) = I_{mc}^0 \\ \dot{I}_{mA_1}(t) = s_{mA_1}(t) + \omega_{RA_1} I_{RA_1}(t) + C_{rA_1}(t) - P_{mA_1}(t) - \omega_{m_1} I_{mA_1}(t) & I_{mA_1}(0) = I_{mA_1}^0 \\ \dot{I}_{md}(t) = s_{md}(t) + C_{rd}(t) - P_{md}(t) & I_{md}(0) = I_{md}^0 \\ \dot{I}_{mA}(t) = s_{mA}(t) + \omega_{RA} I_{RA}(t) - P_{mA}(t) - \omega_{m_2} I_{mA}(t) & I_{mA}(0) = I_{mA}^0 \\ \dot{I}_{RA_1}(t) = \omega_{m_1} I_{mA_1}(t) - \omega_{RA_1} I_{RA_1}(t) - \omega_{CA_1} I_{RA_1}(t) - P_{dA_1}(t) & I_{RA_1}(0) = I_{RA_1}^0 \\ \dot{I}_{RA}(t) = \omega_{m_2} I_{mA}(t) + R(t) - \omega_{RA_2} I_{RA_1}(t) - \omega_{CA_2} I_{RA}(t) - P_{dA}(t) & I_{RA}(0) = I_{RA}^0 \end{cases} \quad (12)$$

By placing the relationships category (10) and (11) into the relationship category (12), the following relationships are obtained:

$$\begin{cases} \dot{I}_{mb}(t) = s_{mb}(t) + \alpha \omega_{CA_1} I_{RA_1}(t) - P_{mb}(t) & I_{mb}(0) = I_{mb}^0 \\ \dot{I}_{mc}(t) = s_{mc}(t) + \beta \omega_{CA_1} I_{RA_1}(t) - P_{mc}(t) & I_{mc}(0) = I_{mc}^0 \\ \dot{I}_{mA_1}(t) = \frac{1}{2\alpha} P_{mb}(t) + \frac{1}{2\beta} P_{mc}(t) + \omega_{RA_1} I_{RA_1}(t) + \delta \omega_{CA_2} I_{RA_2}(t) - P_{mA_1}(t) - \omega_{m_1} I_{mA_1}(t) & I_{mA_1}(0) = I_{mA_1}^0 \\ \dot{I}_{md}(t) = s_{md}(t) + \gamma \omega_{CA} I_{RA}(t) - P_{md}(t) & I_{md}(0) = I_{md}^0 \\ \dot{I}_{mA}(t) = \frac{1}{2\gamma} P_{md}(t) + \frac{1}{2\delta} P_{mA_1}(t) + \omega_{RA} I_{RA}(t) - P_{mA}(t) - \omega_{m_2} I_{mA}(t) & I_{mA}(0) = I_{mA}^0 \\ \dot{I}_{RA_1}(t) = \omega_{m_1} I_{mA_1}(t) - \omega_{RA_1} I_{RA_1}(t) - \omega_{CA_1} I_{RA_1}(t) - \omega_{dA_1} I_{RA_1}(t) & I_{RA_1}(0) = I_{RA_1}^0 \\ \dot{I}_{RA}(t) = \omega_{m_2} I_{mA}(t) + R(t) - \omega_{RA} I_{RA_1}(t) - \omega_{CA} I_{RA}(t) - \omega_{dA} I_{RA}(t) & I_{RA}(0) = I_{RA}^0 \end{cases} \quad (13)$$

Column matrices ($\tilde{x}(t)$ and $\tilde{u}(t)$) including state and control variables are defined as follows:

$$\tilde{x}(t) = [I_{mb}(t) \ I_{mc}(t) \ I_{mA_1}(t) \ I_{md}(t) \ I_{mA}(t) \ I_{RA_1}(t) \ I_{RA}(t)]^T$$

$$\tilde{u}(t) = [s_{mb}(t) \ s_{mc}(t) \ s_{md}(t) \ P_{mb}(t) \ P_{mc}(t) \ P_{mA_1}(t) \ P_{md}(t) \ P_{mA}(t) \ R(t)]^T$$

The matrix A whose entries form the coefficients of state variables in the relationships category (13), is defined as follows:

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & \alpha \omega_{CA_1} & 0 \\ 0 & 0 & 0 & 0 & 0 & \beta \omega_{CA_1} & 0 \\ 0 & 0 & -\omega_{m_1} & 0 & 0 & \omega_{RA_1} & \delta \omega_{CA_2} \\ 0 & 0 & 0 & 0 & 0 & 0 & \gamma \omega_{CA} \\ 0 & 0 & 0 & 0 & -\omega_{m_2} & 0 & \omega_{RA} \\ 0 & 0 & \omega_{m_1} & 0 & 0 & -(\omega_{RA_1} + \omega_{CA_1} + \omega_{dA_1}) & 0 \\ 0 & 0 & 0 & 0 & \omega_{m_2} & 0 & -(\omega_{RA} + \omega_{CA} + \omega_{dA}) \end{bmatrix}$$

And the matrix B whose entries form the coefficients of control variables in the relationships category (13), is defined as follows:

$$B = \begin{bmatrix} 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2\alpha} & \frac{1}{2\beta} & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2\delta} & \frac{1}{2\gamma} & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

According to A and B matrices, it could be stated:

$$\dot{\tilde{x}}(t) = A\tilde{x}(t) + B\tilde{u}(t), \quad \tilde{x}(0)\tilde{x}_0 \quad (14)$$

To obtain the target values of the state and control variables, the relationship is defined as follows:

$$\Delta f(t) = f(t) - \hat{f}(t) \quad (15)$$

Where f is the control or state variable and $\hat{f}$ is the target value of f . So we define $x(t)$ and $u(t)$ matrices as:

$$x(t) = [\Delta I_{mb}(t) \ \Delta I_{mc}(t) \ \Delta I_{mA_1}(t) \ \Delta I_{md}(t) \ \Delta I_{mA}(t) \ \Delta I_{RA_1}(t) \ \Delta I_{RA}(t)]^T$$

$$u(t) = [\Delta S_{mb}(t) \ \Delta S_{mc}(t) \ \Delta S_{md}(t) \ \Delta P_{mb}(t) \ \Delta P_{mc}(t) \ \Delta P_{mA_1}(t) \ \Delta P_{md}(t) \ \Delta P_{mA}(t) \ \Delta R(t)]^T$$

The goals for the state and control variables are the constraints that apply to these variables in the model. The purpose of producing, remanufacturing, or recycling items is the finite capacity for which the workstation is intended, and the purpose of inventories is the finite capacity that should be considered for warehouses. Therefore, when the objective function is a minimization type of Δf_i , the objective function is actually to converge between the control and the state variables with their target values.

Now, considering the above explanation and the set of equations (13), the problem of linear binomial optimal control with finite time is defined as follows:

$$\begin{aligned} \min & k_1(\Delta I_{mb}(T))^2 + k_2(\Delta I_{mc}(T))^2 + k_3(\Delta I_{mA_1}(T))^2 + k_4(\Delta I_{md}(T))^2 + k_5(\Delta I_{mA}(T))^2 \\ & + k_6(\Delta I_{RA_1}(T))^2 + k_7(\Delta I_{RA}(T))^2 \\ & \int_0^T [q_1(\Delta I_{mb}(t))^2 + q_2(\Delta I_{mc}(t))^2 + q_3(\Delta I_{mA_1}(t))^2 + q_4(\Delta I_{md}(t))^2 + q_5(\Delta I_{mA}(t))^2 \\ & + q_6(\Delta I_{RA_1}(t))^2 + q_7(\Delta I_{RA}(t))^2 + r_1\Delta S_{mb}(t) + r_2\Delta S_{mc}(t) + r_3\Delta S_{md}(t) \\ & + r_4\Delta P_{mb}(t) + r_5\Delta P_{mc}(t) + r_6\Delta P_{mA_1}(t) + r_7\Delta P_{md}(t) + r_8\Delta P_{mA}(t) + r_9\Delta R(t)]dt \end{aligned}$$

St.

(16)

$$\begin{cases}
\dot{\Delta I}_{mb}(t) = \Delta s_{mb}(t) + \alpha \omega_{CA_1} \Delta I_{RA_1}(t) - \Delta P_{mb}(t) & \Delta I_{mb}(0) = \Delta I_{mb}^0 \\
\dot{\Delta I}_{mc}(t) = \Delta s_{mc}(t) + \beta \omega_{CA_1} \Delta I_{RA_1}(t) - \Delta P_{mc}(t) & \Delta I_{mc}(0) = \Delta I_{mc}^0 \\
\dot{\Delta I}_{mA_1}(t) = \frac{1}{2\alpha} \Delta P_{mb}(t) + \frac{1}{2\beta} \Delta P_{mc}(t) + \omega_{RA_1} \Delta I_{RA_1}(t) + \delta \omega_{CA_2} \Delta I_{RA}(t) - \Delta P_{mA_1}(t) - \omega_{m_1} \Delta I_{mA_1}(t) & \Delta I_{mA_1}(0) = \Delta I_{mA_1}^0 \\
\dot{\Delta I}_{md}(t) = \Delta s_{md}(t) + \gamma \omega_{CA} \Delta I_{RA}(t) - \Delta P_{md}(t) & \Delta I_{md}(0) = \Delta I_{md}^0 \\
\dot{\Delta I}_{mA}(t) = \frac{1}{2\gamma} \Delta P_{md}(t) + \frac{1}{2\delta} \Delta P_{mA_1}(t) + \omega_{RA} \Delta I_{RA}(t) - \Delta P_{mA}(t) - \omega_{m_2} \Delta I_{mA}(t) & \Delta I_{mA}(0) = \Delta I_{mA}^0 \\
\dot{\Delta I}_{RA_1}(t) = \omega_{m_1} \Delta I_{mA_1}(t) - \omega_{RA_1} \Delta I_{RA_1}(t) - \omega_{CA_1} \Delta I_{RA_1}(t) - \omega_{dA_1} \Delta I_{RA_1}(t) & \Delta I_{RA_1}(0) = \Delta I_{RA_1}^0 \\
\dot{\Delta I}_{RA}(t) = \omega_{m_2} \Delta I_{mA}(t) + \Delta R(t) - \omega_{RA} \Delta I_{RA_1}(t) - \omega_{CA} \Delta I_{RA}(t) - \omega_{dA} \Delta I_{RA}(t) & \Delta I_{RA}(0) = \Delta I_{RA}^0
\end{cases}$$

Where k_i and q_i ($i = (1, 2, \dots, 7)$) and also r_i ($j = (1, 2, \dots, 11)$) are non-negative real numbers that are considered as penalty coefficients of the deviation of the variables from their target values.

As is known, the matrix entries A and B are coefficients of the state and control variables of the model constraints (16).

2.2. Model two: The mode with considering the lead time

In this model, the lead time is considered in each stage of production. Therefore, the production lead time for the work in process (A_1) is τ_{A_1} and for Product A is defined as τ_A .

$$\begin{aligned}
I_{mA_1}(t) &= \alpha \alpha^2 I_{mb}(t - \tau_{A_1}) + \alpha \beta^2 I_{mc}(t - \tau_{A_1}) + \omega_{RA_1} I_{RA_1}(t) + \delta \omega_{CA} I_{RA}(t) - P_{mA_1}(t) \\
&\quad - \omega_{m_1} I_{mA_1}(t) \quad I_{mA_1}(0) = I_{mA_1}^0
\end{aligned} \quad (17)$$

The following relationship will be obtained considering the lead time for the product A :

$$\begin{aligned}
\dot{I}_{mA}(t) &= \frac{\dot{b}}{2} I_{md}(t - \tau_A) + \frac{\dot{b}}{2} I_{mA_1}(t - \tau_A) + \omega_{RA} I_{RA}(t) \\
&\quad - P_{mA}(t) - \omega_{m_2} I_{mA}(t) \quad I_{mA}(0) = I_{mA}^0
\end{aligned} \quad (18)$$

Since the above two equations are a linear system of delayed differential equations, we will have the equation (13) using Taylor expansion as follows:

$$\begin{cases}
I_{mb}(t) = s_{mb}(t) + \alpha \omega_{CA_1} I_{RA_1}(t) - P_{mb}(t) & I_{mb}(0) = I_{mb}^0 \\
I_{mc}(t) = s_{mc}(t) + \beta \omega_{CA_1} I_{RA_1}(t) - P_{mc}(t) & I_{mc}(0) = I_{mc}^0 \\
I_{mA_1}(t) = \alpha \alpha^2 (I_{mb}(t) - \tau_{A_1} \dot{I}_{mb}(t)) + \alpha \beta^2 (I_{mc}(t) - \tau_{A_1} \dot{I}_{mc}(t)) + \omega_{RA_1} I_{RA_1}(t) + \delta \omega_{CA} I_{RA}(t) \\
\quad - P_{mA_1}(t) - \omega_{m_1} I_{mA_1}(t) & I_{mA_1}(0) = I_{mA_1}^0 \\
I_{md}(t) = s_{md}(t) + \gamma \omega_{CA} \Delta I_{RA}(t) - b \gamma I_{md}(t) & I_{md}(0) = I_{md}^0 \\
I_{mA}(t) = \frac{\dot{b}}{2} (I_{md}(t) - \tau_A \dot{I}_{md}(t)) + \frac{\dot{b}}{2} (I_{mA_1}(t) - \tau_A \dot{I}_{mA_1}(t)) + \omega_{RA} I_{RA}(t) - P_{mA}(t) - \omega_{m_2} I_{mA}(t) & I_{mA}(0) = I_{mA}^0 \\
I_{RA_1}(t) = \omega_{m_1} \Delta I_{mA_1}(t) - \omega_{RA_1} \Delta I_{RA_1}(t) - \omega_{CA_1} I_{RA_1}(t) - \omega_{dA_1} \Delta I_{RA_1}(t) & I_{RA_1}(0) = I_{RA_1}^0 \\
I_{RA}(t) = \omega_{m_2} I_{mA}(t) + R(t) - \omega_{RA} I_{RA_1}(t) - \omega_{CA} I_{RA}(t) - \omega_{dA} I_{RA}(t) & I_{RA}(0) = I_{RA}^0
\end{cases} \quad (19)$$

The above equation will be converted as follows after simplification, by placing the first and second equations in the third equation:

$$\begin{aligned} \dot{I}_{mA_1}(t) = & (a\alpha^2 + \tau_{A_1} a^2 \alpha^3) I_{mb}(t) - a\alpha^2 \tau_{A_1} (s_{mb}(t) + (-\tau_{A_1} a\alpha^3 \omega_{CA_1} - a\beta^3 \tau_{A_1} \omega_{CA_1} \\ & + \omega_{RA_1}) I_{RA_1}(t) + (a\beta^2 \\ & + \tau_{A_1} a^2 \beta^3) I_{mc}(t) - \tau_{A_1} a\beta^2 (s_{mc}(t) + \delta \omega_{CA} I_{RA}(t) - P_{mA_1}(t) \\ & - \omega_{m_1} I_{mA_1}(t) \quad I_{mA_1}(0) = I_{mA_1}^0 \end{aligned} \quad (20)$$

And putting the equation (20) and the fourth equation of the equation group (19) in the fifth equation will transform the above equation as follows after simplification:

$$\begin{aligned} \dot{I}_{mA}(t) = & \left(\frac{\dot{b}}{2} - \frac{\dot{b}^2}{2} \gamma \tau_A \right) I_{md}(t) - \frac{\dot{b}}{2} \tau_A s_{md}(t) + \left(\frac{\dot{b}}{2} \gamma \omega_{CA} \tau_A - \frac{\dot{b}}{2} \tau_A \delta \omega_{CA} + \omega_{RA} \right) I_{RA}(t) \\ & + \left(\frac{\dot{b}}{2} + \frac{\dot{b}^2}{2} \tau_A \omega_{m_1} \right) I_{mA_1}(t) - \frac{\dot{b}}{2} \tau_A (a\alpha^2 + \tau_{A_1} a^2 \alpha^3) I_{mb}(t) \\ & + \frac{\dot{b}}{2} \tau_A a\alpha^2 \tau_{A_1} s_{mb}(t) + \frac{\dot{b}}{2} \tau_A (\tau_{A_1} a\alpha^3 \omega_{CA_1} + a\beta^3 \tau_{A_1} \omega_{CA_1} - \omega_{RA_1}) I_{RA_1}(t) \\ & - \frac{\dot{b}}{2} \tau_A (a\beta^2 + \tau_{A_1} a^2 \beta^3) I_{mc}(t) + \frac{\dot{b}}{2} a\beta^2 \tau_A \tau_{A_1} s_{mc}(t) + \frac{\dot{b}}{2} \tau_A P_{mA_1}(t) \\ & - P_{mA}(t) - \omega_{m_2} I_{mA}(t) \quad I_{mA}(0) = I_{mA}^0 \end{aligned} \quad (21)$$

Therefore, by placing equations (20) and (21), the equation groups (19) will be as follows:

$$\begin{cases} \dot{I}_{mb}(t) = s_{mb}(t) + \alpha \omega_{CA_1} I_{RA_1}(t) - P_{mb}(t) & I_{mb}(0) = I_{mb}^0 \\ \dot{I}_{mc}(t) = s_{mc}(t) + \beta \omega_{CA_1} I_{RA_1}(t) - P_{mc}(t) & I_{mc}(0) = I_{mc}^0 \\ \dot{I}_{mA_1}(t) = (a\alpha^2 + \tau_{A_1} a^2 \alpha^3) I_{mb}(t) - a\alpha^2 \tau_{A_1} s_{mb}(t) + (-\tau_{A_1} a\alpha^3 \omega_{CA_1} - a\beta^3 \tau_{A_1} \omega_{CA_1} + \omega_{RA_1}) I_{RA_1}(t) \\ + (a\beta^2 + \tau_{A_1} a^2 \beta^3) I_{mc}(t) - a\beta^2 \tau_{A_1} s_{mc}(t) + \delta \omega_{CA} I_{RA}(t) - P_{mA_1}(t) - \omega_{m_1} I_{mA_1}(t) \\ \dot{I}_{md}(t) = s_{md}(t) + \gamma \omega_{CA} I_{RA}(t) - P_{md}(t) & I_{md}(0) = I_{md}^0 \\ \dot{I}_{mA}(t) = \left(\frac{\dot{b}}{2} - \frac{\dot{b}^2}{2} \gamma \tau_A \right) I_{md}(t) - \frac{\dot{b}}{2} \tau_A s_{md}(t) + \left(\frac{\dot{b}}{2} \gamma \omega_{CA} \tau_A - \frac{\dot{b}}{2} \tau_A \delta \omega_{CA} + \omega_{RA} \right) I_{RA}(t) \\ + \left(\frac{\dot{b}}{2} + \frac{\dot{b}^2}{2} \tau_A \omega_{m_1} \right) I_{mA_1}(t) - \frac{\dot{b}}{2} \tau_A (a\alpha^2 + \tau_{A_1} a^2 \alpha^3) I_{mb}(t) \\ + \frac{\dot{b}}{2} \tau_A a\alpha^2 \tau_{A_1} s_{mb}(t) + \frac{\dot{b}}{2} \tau_A (\tau_{A_1} a\alpha^3 \omega_{CA_1} + a\beta^3 \tau_{A_1} \omega_{CA_1} - \omega_{RA_1}) I_{RA_1}(t) \\ - \frac{\dot{b}}{2} \tau_A (a\beta^2 + \tau_{A_1} a^2 \beta^3) I_{mc}(t) + \frac{\dot{b}}{2} a\beta^2 \tau_A \tau_{A_1} s_{mc}(t) + \frac{\dot{b}}{2} \tau_A P_{mA_1}(t) - P_{mA}(t) - \omega_{m_2} I_{mA}(t) & I_{mA}(0) = I_{mA}^0 \\ \dot{I}_{RA_1}(t) = \omega_{m_1} I_{mA_1}(t) - \omega_{RA_1} I_{RA_1}(t) - \omega_{CA_1} I_{RA_1}(t) - \omega_{dA_1} I_{RA_1}(t) & I_{RA_1}(0) = I_{RA_1}^0 \\ \dot{I}_{RA}(t) = \omega_{m_2} I_{mA}(t) + R(t) - \omega_{RA} I_{RA_1}(t) - \omega_{CA} I_{RA}(t) - \omega_{dA} I_{RA}(t) & I_{RA}(0) = I_{RA}^0 \end{cases} \quad (22)$$

The column matrices ($\tilde{x}(t)$ and $\tilde{u}(t)$), which include the state and control variables, are defined as follows:

$$\tilde{x}(t) = [I_{mb}(t) \ I_{mc}(t) \ I_{mA_1}(t) \ I_{md}(t) \ I_{mA}(t) \ I_{RA_1}(t) \ I_{RA}(t)]^T$$

$$\tilde{u}(t) = [s_{mb}(t) \ s_{mc}(t) \ s_{md}(t) \ P_{mb}(t) \ P_{mc}(t) \ P_{mA_1} \ P_{md}(t) \ P_{mA}(t) \ R(t)]^T$$

The matrix $\hat{A}$ whose entries form the coefficients of state variables in the relationships category (27), is defined as follows:

$$A' = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & \alpha\omega_{CA1} & 0 \\ 0 & 0 & 0 & 0 & 0 & \beta\omega_{CA1} & 0 \\ (a\alpha^2 + \tau_{A1}a^2\alpha^3) & (a\beta^2 + \tau_{A1}a^2\beta^3) & -\omega_{m1} & 0 & 0 & -(\tau_{A1}a\alpha^3\omega_{CA1} + a\beta^3\tau_{A1}\omega_{CA1} - \omega_{RA1}) & \delta\omega_{CA} \\ 0 & 0 & 0 & 0 & 0 & 0 & \gamma\omega_{CA} \\ -\frac{b'}{2}\tau_A(a\alpha^2 + \tau_{A1}a^2\alpha^3) & -\frac{b'}{2}\tau_A(a\beta^2 + \tau_{A1}a^2\beta^3) & (\frac{b'}{2} + \frac{b'}{2}\tau_A\omega_{m1}) & (\frac{b'}{2} - \frac{b'}{2}\gamma\tau_A) & -\omega_{m2} & \frac{b'}{2}\tau_A(\tau_{A1}a\alpha^3\omega_{CA1} + a\beta^3\tau_{A1}\omega_{CA1} - \omega_{RA1}) & (\frac{b'}{2}\gamma\omega_{CA}\tau_A - \frac{b'}{2}\tau_A\delta\omega_{CA} + \omega_{RA}) \\ 0 & 0 & \omega_{m1} & 0 & 0 & -(\omega_{RA1} + \omega_{CA1} + \omega_{DA1}) & 0 \\ 0 & 0 & 0 & 0 & \omega_{m2} & 0 & -(\omega_{RA} + \omega_{CA} + \omega_{DA}) \end{bmatrix}$$

The matrix $\hat{B}$ whose entries form the coefficients of control variables in the relationships category (27), is defined as follows:

$$B' = \begin{bmatrix} 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ -a\alpha^2\tau_{A1} & -a\beta^2\tau_{A1} & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 \\ \frac{b'}{2}a\alpha^2\tau_A\tau_{A1} & \frac{b'}{2}a\beta^2\tau_A\tau_{A1} & -\frac{b'}{2}\tau_A & 0 & 0 & \frac{b'}{2}\tau_A & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

3. Model solving

In this section, the system of differential equations related to the proposed model will be derived and then solved.

If $Q = \text{diag}\{q_i\}$, $K = \text{diag}\{k_i\}$ and $R = \text{diag}\{r_j\}$ is defined for $i = 1, 2, \dots, 7$ and also $j = 1, 2, \dots, 9$ is defined as diagonal matrices that are penalty factors, the model (15) can then be summarized as follows:

$$\text{Minimize } x^T(T)Kx(T) + \int_0^T [x^T(t)Qx(t) + u^T(t)Ru(t)]dt \quad (23)$$

st

$$\dot{x}(t) = Ax(t) + Bu(t), \quad x(0) = x^0$$

Where K and Q are both the real diagonal matrices from the 7th grade and R is the real diagonal matrices from the 9th grade with positive entries.

Adequate optimization conditions are usually obtained for optimal control problems using the Hamiltonian. Hamiltonian should first be identified as follows to achieve optimum, sufficient conditions:

$$H(x(t), u(t), \lambda(t), t) = x^T(t)Qx(t) + u^T(t)Ru(t) + \lambda^T(t)[Ax(t) + Bu(t)] \quad (24)$$

Based on the maximum principle, the optimum conditions for the problem (23) are as follows:

$$\begin{aligned}
\frac{\partial H(x(t), u(t), \lambda(t), t)}{\partial x} &= \dot{\lambda}(t), \lambda(T) = 2Kx(T) \\
\frac{\partial H(x(t), u(t), \lambda(t), t)}{\partial \lambda} &= \dot{x}(t), x(0) = x^0 \\
\frac{\partial H(x(t), u(t), \lambda(t), t)}{\partial u} &= 0
\end{aligned} \tag{25}$$

Or its equivalent can be written as follows:

$$\begin{aligned}
-\dot{\lambda}(t) &= 2Qx(t) + A^t \lambda(t), \quad \lambda(T) = 2Kx(T) \\
\dot{x}(t) &= Ax(t) + Bu(t), \quad x(0) = x^0 \\
u(t) &= -\frac{1}{2}R^{-1}B^t \lambda(t)
\end{aligned} \tag{26}$$

From the third equation of the equation category (26), the optimal control law can be obtained. Therefore, the system of differential equations (26) is converted as follows:

$$\begin{aligned}
\dot{\lambda}(t) &= -(2Qx(t) + A^t \lambda(t)), \quad \lambda(T) = 2Kx(T) \\
\dot{x}(t) &= Ax(t) - \frac{1}{2}BR^{-1}B^t \lambda(t) \quad x(0) = x^0
\end{aligned} \tag{27}$$

It should be noted that the equations category (26) as well as (27) are optimum conditions. To ensure that the control obtained $u^*(t)$ meets the required optimization conditions, which is optimize the minimization of the problem (23), the following matrix must be defined positively (Subbaram Naido, 2002).

$$\Pi = \begin{bmatrix} \frac{\partial^2 H}{\partial x^2} & \frac{\partial^2 H}{\partial x \partial u} \\ \frac{\partial^2 H}{\partial u \partial x} & \frac{\partial^2 H}{\partial u^2} \end{bmatrix} \tag{28}$$

Which may be written as follows:

$$\Pi = \begin{bmatrix} 2Q & 0 \\ 0 & 2R \end{bmatrix}$$

However, since diagonal matrices (R and Q) have positive entries, the matrix Π is positive and therefore the control obtained $u^*(t)$ has the necessary optimization conditions.

4. Numerical simulation

The model was used by the Mashhad Panel Barsava Manufacturing Company to validate the proposed models and assess their applicability. The company's 3D panels are simulated in Figure 3, in the three-stage production-inventory system. MATLAB 2017 software will solve the final optimal control model to obtain the necessary results and objectives set for the research.

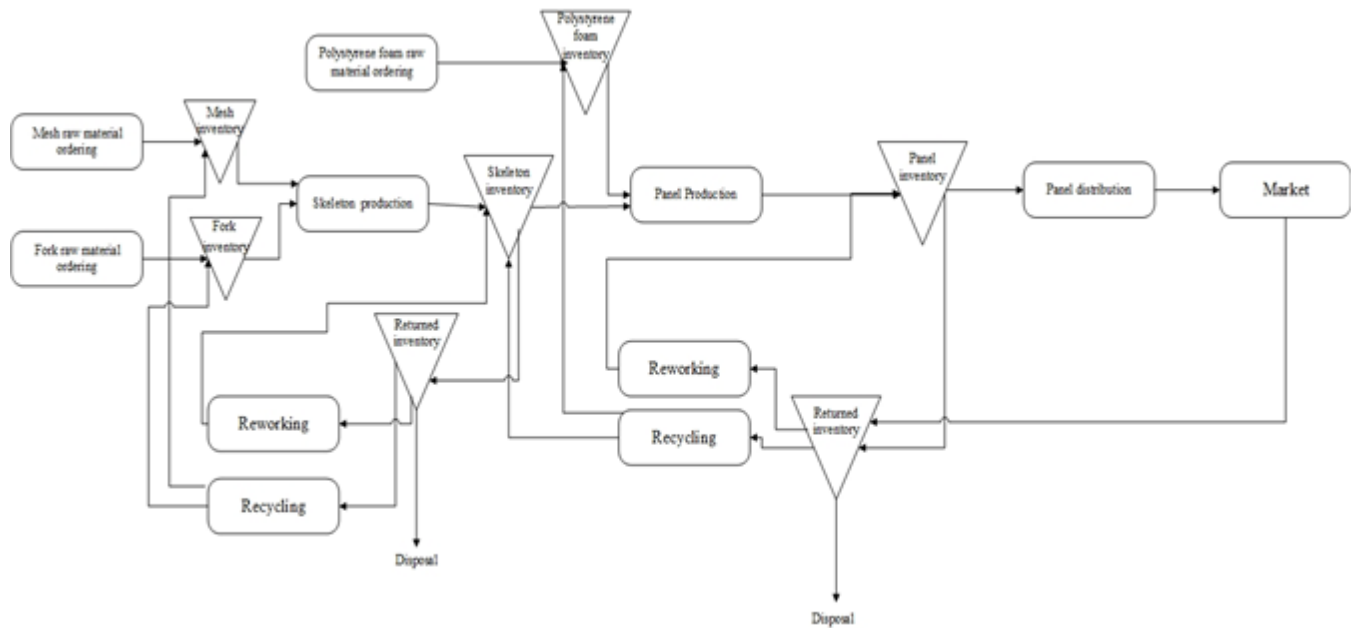


Figure 3. Production-inventory model of 3D panel

Each product often requires a specific process and production line. Mashhad Panel Barsava Manufacturing Company also has its own production process for its products. To produce 3D panels, first the raw materials for mesh ($s_{mb}(t)$) and fork ($s_{mc}(t)$) are ordered. The raw materials are then formed into a skeleton after welding. The amount of skeletal inventory is shown by $I_{mA_1}(t)$. At this stage, another raw material called polystyrene foam will be ordered to produce the 3D panel $s_{md}(t)$. The polystyrene foam ($I_{md}(t)$) and skeleton ($I_{mA_1}(t)$) inventory will be sent to ($P_{md}(t)$) and ($P_{mA_1}(t)$) in order to produce 3D panels, respectively. Some produced skeleton inventory may be refunded with ω_{m_1} rate. Among the returned skeletons, some will be recycled at the ω_{CA_1} rate and after separation, will be added to the mesh and fork inventory with $C_{rb}(t)$ and $C_{rc}(t)$, respectively. And some will be sent at the ω_{mA_1} rate for reworking. After combining polystyrene foam with the work in process in the previous stage, 3D panel will be produced. The production order of 3D panels is equal to ($s_{mA}(t)$) and from their inventory ($I_{mA}(t)$), some may be returned at the ω_{m_2} rate and the rest will be sent to the market as demand ($D(t)$) for distribution. From the returned 3D panel inventory ($I_{RA}(t)$), some will be sent at the ω_{RA} rate for reworking and will be added to the 3D panel inventory after reworking. Some will be recycled at the ω_{CA} rate that will be added to the polystyrene foam ($I_{md}(t)$) and skeleton ($I_{mA_1}(t)$) inventories. The rest will be disposed of at the ω_{dA} rate of perishable goods $\omega_{dA}(t)I_{RA}(t)$. Among the panels distributed in the market, the $R(t)$ is returned as much.

Two models will be introduced next. The lead time in each production stage will be considered as zero in the first model, and in the second model the lead time for each production stage will be considered. It is worth noting that the parameters used in both models are similar.

The values of the parameters and the beginning inventory amount related to Mashhad Panel Barsava Manufacturing Company are specified in Tables 2 and 3, respectively.

Table 2. Constant parameters

parameter	ω_{m1}	ω_{m2}	ω_{RA1}	ω_{RA}	ω_{CA1}	ω_{CA}	ω_{dA1}	ω_{dA}	α	β	γ	δ	T	t	τ_{A1}	τ_A	a	b
Value	0.05	0.03	0.8	0.7	0.15	0.2	0.05	0.1	2	20	1	1	6	1	0.1	0.05	0.01	0.1

Table 3. Inventory values at the beginning of the period

Variable	I^0_{mb}	I^0_{mc}	I^0_{md}	$I^0_{mA_1}$	I^0_{mA}	$I^0_{RA_1}$	I^0_{RA}
Value	100	100	20	20	5	3	4

4.1. First mode: Production-inventory optimal control model of 3D panels without considering the lead time

By placing the specified parameters in tables 2 and 3 in the category of equation (13), a dynamic system is obtained in which the coefficients of state and control variables form the entries of matrices A and B, which are defined as follows:

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0.3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3 & 0 \\ 0 & 0 & -0.05 & 0 & 0 & 0.8 & 0.7 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.2 \\ 0 & 0 & 0 & 0 & -0.03 & 0 & 0.7 \\ 0 & 0 & 0.05 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0.03 & 0 & -1 \end{bmatrix} \quad B = \begin{bmatrix} 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{4} & \frac{1}{40} & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2} & \frac{1}{2} & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Now consider the linear binomial optimal control (16). If the present penalty factors are defined as

$Q = \text{diag}\{15, 16, 10, 14, 3, 8, 9\}$, $K = \text{diag}\{120, 190, 140, 110, 145, 130, 125\}$ and $R =$

$\text{diag}\{2, 6, 4, 5, 2, 2, 1, 1, 2\}$ matrices, the final answer is shown in Figures 4 and 5. Therefore, variables of state and control converge to their target values. Since the state and control functions are the deviation between the answers and their objective functions, according to

Figures 4 and 5, when $\Delta f(t) \rightarrow 0$ ($f(t)$ it can be a state or control variable), it means that $f(t) - \hat{f}(t)$ is convergence to zero or $f(t) \rightarrow \hat{f}(t)$ that means functions (state or control) are convergent according to their purpose. Convergence to predetermined target values means that inventory variables and the level of orders and shipments have reached the desired values for managers to control, which will ultimately reduce costs.

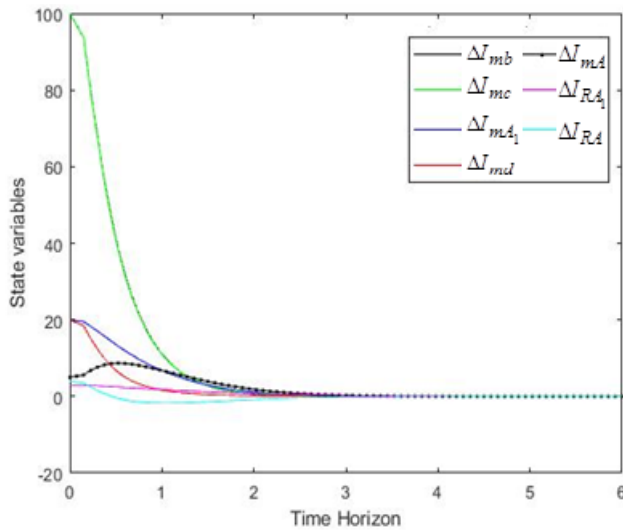


Figure 4. Final solution for state variables (without LTs)

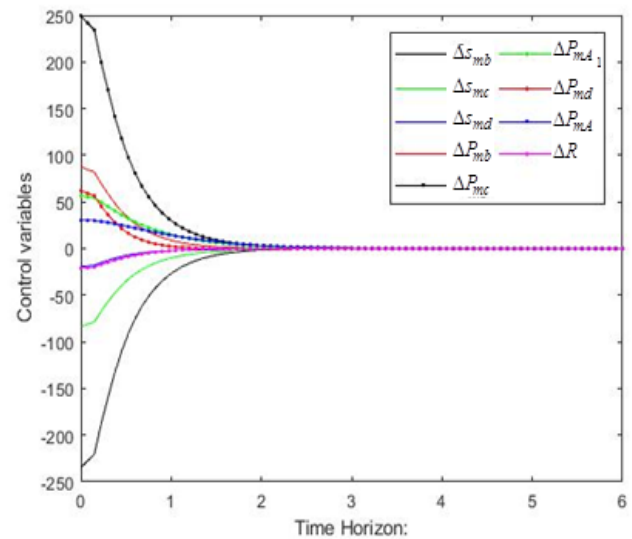


Figure 5. Final solution for control variables (without LTs)

4.2. Second mode: Production-inventory optimal control model of 3D panels with considering the lead time

Now, if the specified parameters in Tables 2 and 3 are included in the delayed optimal control model (22), the matrix of coefficients of the state and control variables $\hat{A}$ and $\hat{B}$ is obtained as

$$A' = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0.3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3 & 0 \\ 0.04008 & 4.08 & -0.05 & 0 & 0 & -0.4012 & 0.2 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.2 \\ -0.001 & -0.81 & 0.0501 & 0.0497 & -0.03 & -0.0017 & 0.7 \\ 0 & 0 & 0.05 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0.03 & 0 & -1 \end{bmatrix} \quad B' = \begin{bmatrix} 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ -0.04 & -4 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0.00001 & 0.001 & -0.0025 & 0 & 0 & 0.0025 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Penalty factors in the current linear binomial optimal control will be considered the same as the previous model, so are defined as $Q = \text{diag}\{15, 16, 10, 14, 3, 8, 9\}$ $K = \text{diag}\{120, 190, 140, 110, 145, 130, 125\}$ and $R = \text{diag}\{2, 6, 4, 5, 2, 2, 1, 1, 2\}$ matrices. The results of solving this model are shown in figures 6 and 7.

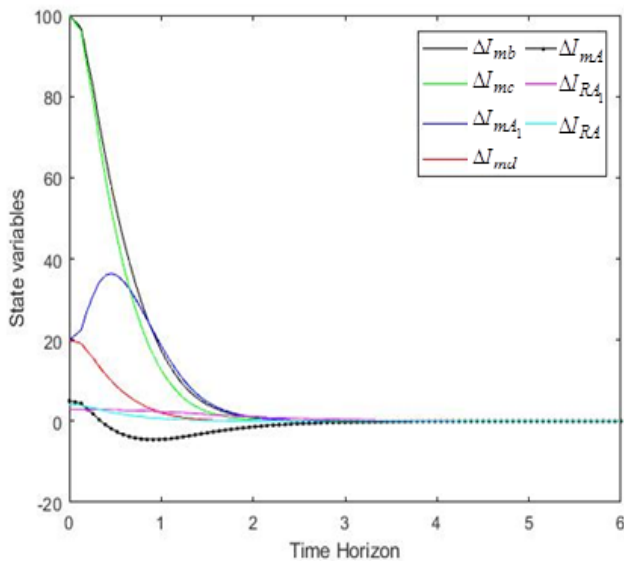


Figure 6. Final solution for state variables (with LTs)

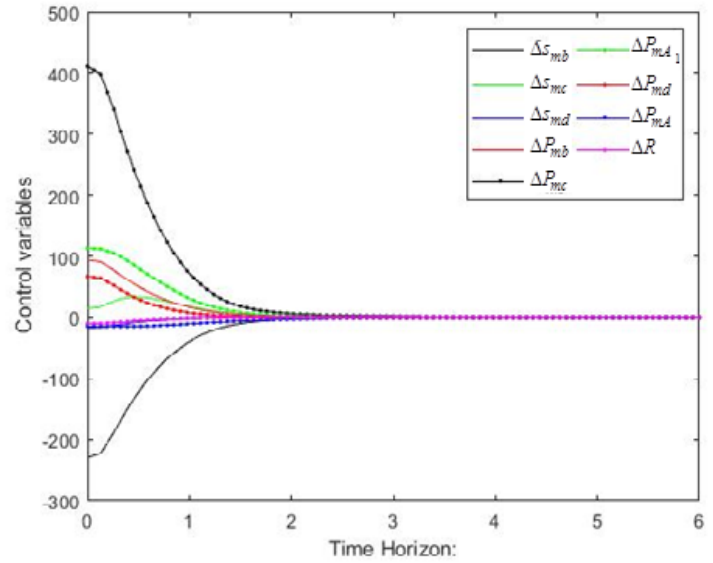


Figure 7. Final solution for control variables (with LTs)

Comparing the two figures 4 and 6, it can be clearly seen that the convergence velocity deviation of the inventories ΔI_{mA_1} , ΔI_{RA_1} , ΔI_{mA} , ΔI_{RA} in the model without delay is greater than the delay mode, but the values of variables ΔI_{mb} , ΔI_{mc} , ΔI_{md} in both delayed and non-delayed modes are almost equal, because at the beginning of each step there is no delay for inventories related to raw materials.

Because there should be no additional fork and mesh raw materials in the skeleton production stage, the diagram related to the deviation from the desired level of the two variables of mesh and fork (ΔI_{mb} , ΔI_{mc}) is equal in the case of no delay. However, if the system is delayed, the convergence deviation rate from the desired level corresponding to the fork is more significant than that of the mesh. The consumption coefficient of the fork is greater than that of the mesh. By comparing the skeletal inventory, it can be seen that the deviation from the desired level is first increased and then converges to zero in the case of a delay system. However, the behavior of the diagram for the raw material of the foam is the same in both models.

Comparing the two figures 5 and 7, which are related to the deviation from the target level of control variables, the convergence rate is higher in the model without delay than the delay model.

Table 4. Comparison of objective function

Problem	Delay	Non-delay
The value of the objective J^*	351890	216878

5. Sensitivity analysis for Q , K and R

In this section, sensitivity analysis is performed in order to show the effect of changes in diagonal matrices Q , K and R and on the values of the objective function in both proposed models. The calculations and results that will be given in the continuation of this section are based on the information in tables 2 and 3.

5.1. Changes in matrix Q entries

As it is clear, by increasing the values q_i for $i = 1, 2, \dots, 7$ its effect on the values of the objective function in the two proposed models have been investigated. The following 4 figures show the convergence status of the state and control variables for values $q_i = 3$ and $q_i = 11$ for $i = 1, 2, \dots, 7$.

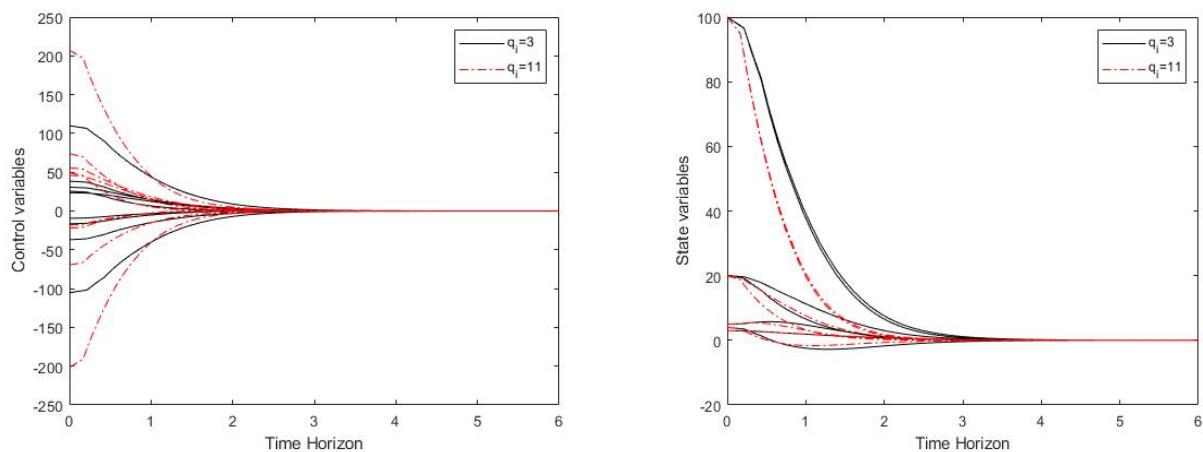


Figure 8. Comparing the convergence speed of state and control variables to their target for different values of q_i (Non Delay)

In general, it can be seen that as the matrix Q values increase, the state variables converge faster. As the matrix Q values increase, the penalty for deviating from the target values of the state variables increases. Because the objective function is a minimization type, $\Delta f(t) = f(t) - \hat{f}(t)$ converges faster to zero for the state variables, or by increasing the matrix Q values, the value of the objective function increases; However, it causes the convergence velocity of state variables to increase (in this example, zero), and convergence occurs faster. In all figures, the variables are grouped for two different values of the matrix.

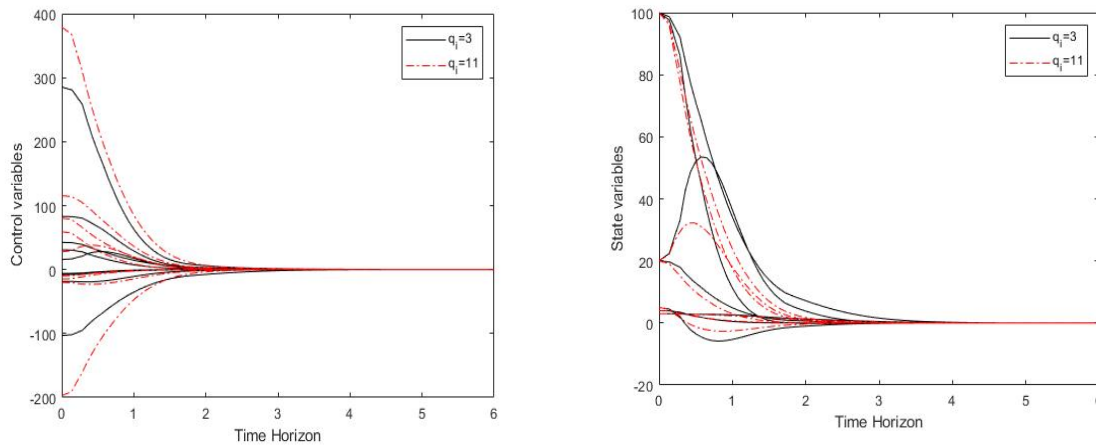


Figure 9. Comparing the convergence speed of state and control variables to their target for different values of q_i (Delay)

As shown in figures 8 and 9, as the values of the matrix increase, the convergence velocity of the control variables is supposed to be slower since the matrix Q is connected to the coefficients of the state variables.

5.2. Changes in matrix K entries

As it is clear, by increasing the values k_i for $i = 1, 2, \dots, 7$, its effect on the values of the objective function in the two proposed models have been investigated. The following 4 figures show the convergence status of the state and control variables for values $k_i = 100$ and $k_i = 140$ for $i = 1, 2, \dots, 7$.

According to the following 4 figures and the table above, the matrix K minimizes the final values of the state variables. Because the state variables' final values are very close to zero, the values of the table have changed slightly.

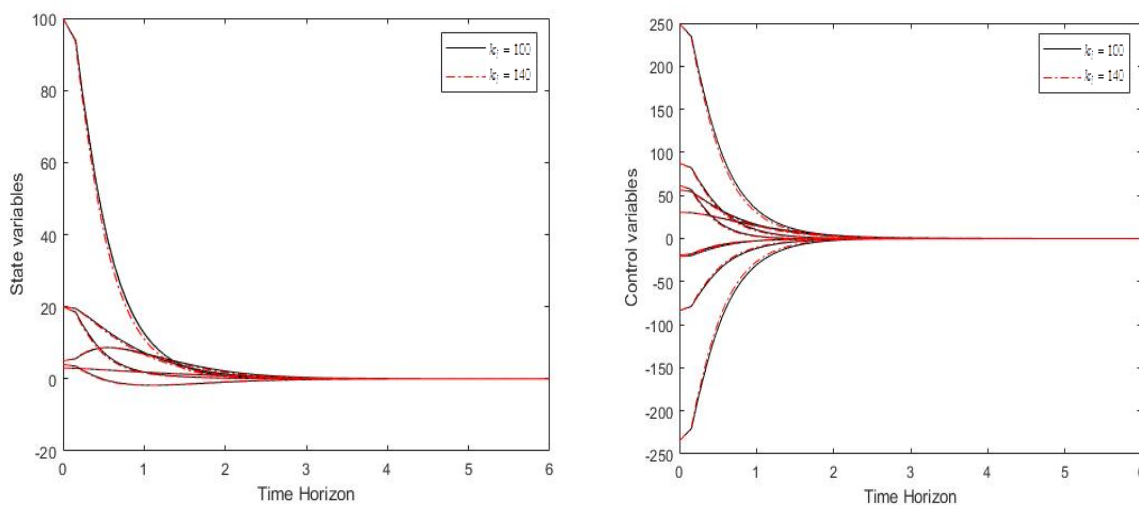


Figure 10. Comparing the convergence speed of state and control variables to their target for different values of k_i (Non-Delay)

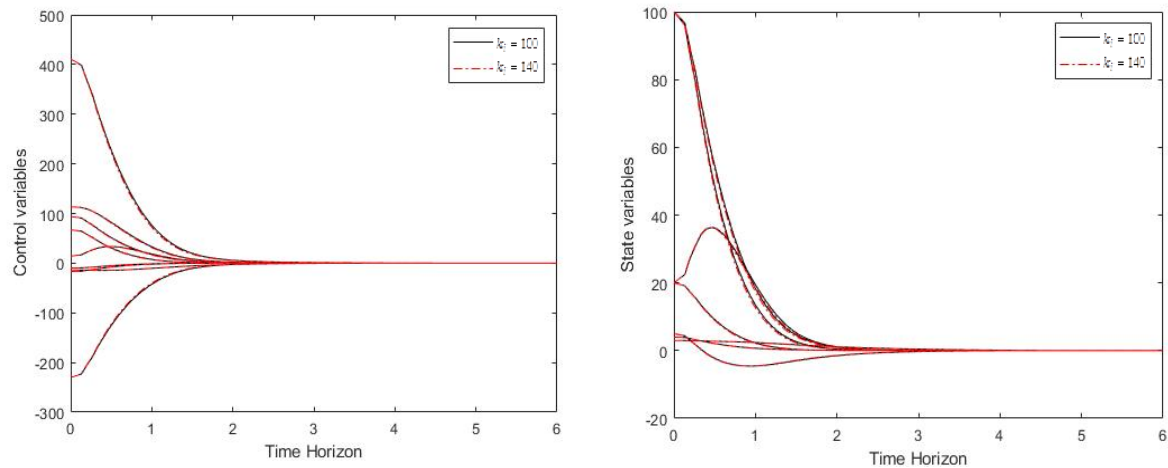


Figure 11. Comparing the convergence speed of state and control variables to their target for different values of k_i (Delay)

5.3. Changes in matrix R entries

As it is clear, by increasing the values r_i for $j = 1, 2, \dots, 9$, its effect on the values of the objective function in the two proposed models have been investigated. The following 4 figures show the convergence status of the state and control variables for values $r_i = 2$ and $r_i = 6$ for $j = 1, 2, \dots, 9$.

Increasing the matrix values as expected increases the objective function value. According to the following statistics, because the matrix is connected to the control variables' coefficients, the control variables converge more rapidly. As shown in Figure 13, since the coefficients of the state variables in the objective function have not changed, the convergence velocity of the state variables has slowed down.

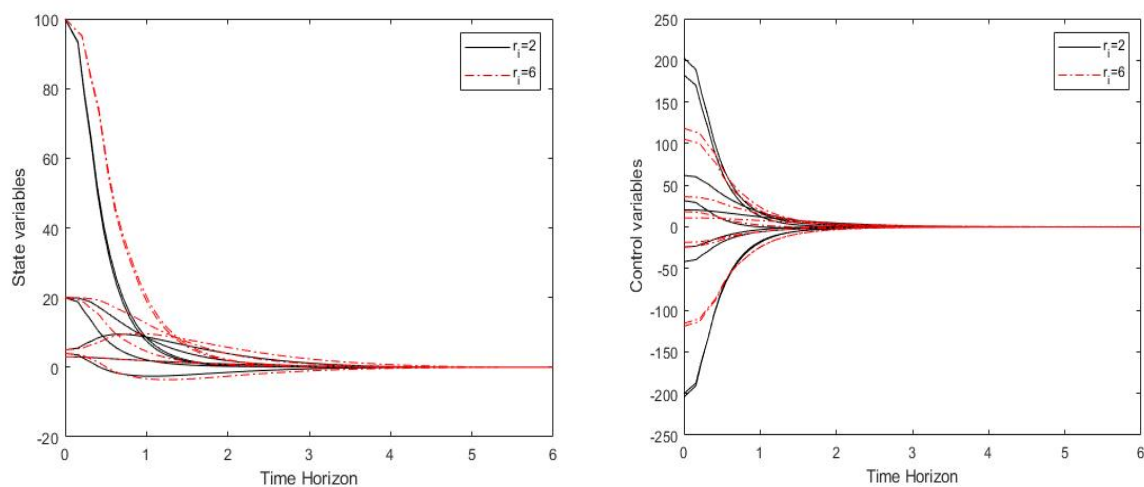


Figure 12. Comparing the convergence speed of state and control variables to their target for different values of r_i (Non-Delay)

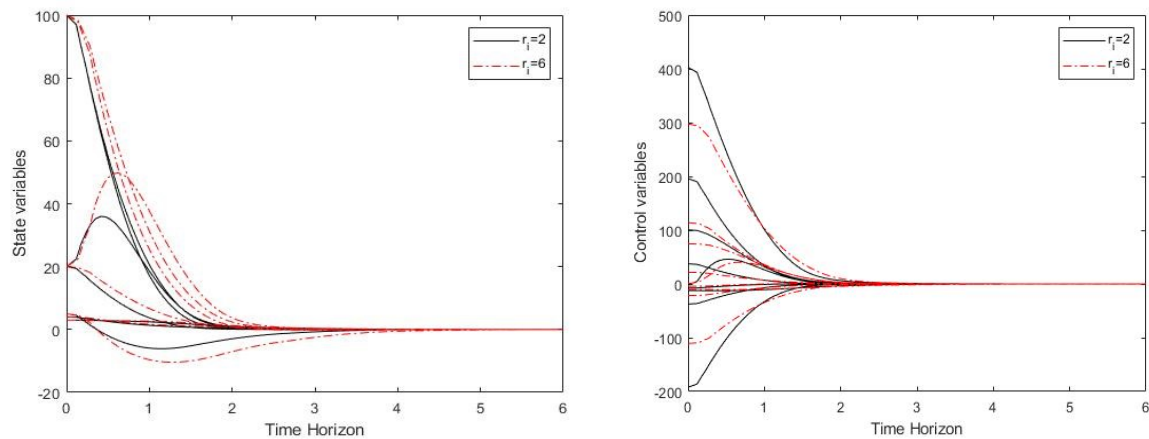


Figure 13. Comparing the convergence speed of state and control variables to their target for different values of r_i (Delay)

Therefore, it is possible to summarize the sensitivity analysis of changes in the values of the coefficients of state and control variables in the objective function as follows:

Table 5. Comparison of sensitivity analysis

Increase in the matrix values	State Variables	Control Variables
Q	Convergence is faster because Q is the coefficient of state variables	Convergence is slower because Q is the coefficient of state variables
R	Convergence is slower because R is the coefficient of control variables	Convergence is faster because R is the coefficient of control variables
K	Not very effective	Not very effective

As mentioned, the matrix Q form the coefficients of the state variables. As the values of the matrix Q entries increase, the state variables will converge faster. Since the matrix R form, the coefficients of the control variables, the control variables' values will converge more rapidly as the values of the matrix R increase. The matrix K is the final coefficients of state variables, and since the final values of state variables are close to zero, they will not have much effect on the values of the objective function.

Therefore, by increasing (in a specific range) the penalty coefficients, the convergence is accelerated. Results indicate that increasing the penalty coefficient in the objective function, accelerates the convergence of the state and control variables.

6. Discussion

As mentioned above, by studying previous research, it is observed that several optimal control models have been proposed to control production and inventory by MRP systems, which often did not take into account the lead time or include the return and reworking stages. In this study, a production-inventory optimal control model is proposed that eliminates this shortcoming.

Model implications are presented in two sections: theoretical implications, which mainly compare the proposed model with previous models, and practical implications, which include cases related to the interpretation of the results of the proposed model.

6.1. Theoretical implications

Based on [Pooya and Pakdaman's \(2019\)](#) proposed approach, an optimal continuous MRP control model can be modified to use computational aspects of CMRP. For example, state variables for inventory stores, control variables for the production, ordering, and demand programs, BOM system, and demand dependence on BOM can all indicate CMRP computational requirements. The current proposed model is a continuous MRP model that considers the delay due to production lead time ([Pooya and Pakdaman, 2019](#)) and a multi-stage production-inventory system ([Pooya and Pakdaman, 2019](#)). Since time is considered a continuous parameter, the lead time is considered in each production stage. Hence, the model is more realistic and feasible for all industries. It is also a proposed model for determining production values at any given time in discrete production processes, such as a workshop, handling the flow, and applying assembly lines.

One of the significant differences between CMRP and DMRP is LT. In the CMRP system, the LT value can be any decimal number, while in the DMRP system provided by [Ignaciuk and Bartoszewicz \(2010\)](#). The LT must be an integer; in this model, if the LT is a non-integer, it should be rounded to the next larger integer. However, the number of orders will be received with a delay. If the LT is rounded to the first smaller number, orders will be received sooner, which will create a surplus inventory and thus increase maintenance costs, and MRP objectives will not be met.

According to the model proposed by [Foul and Tadj \(2007\)](#), returned items will only be returned to the market for reworking. In this article's model, the produced items will be examined before distribution in the market to check the quality of the distributed items. The defective items percentage in the market also be reduced. For this purpose, the returned items should be identified in this stage. Additionally, the return stage for defective items is considered after distribution. Also, in the proposed research model, in addition to reconstruction, the recycling of items is considered. However, in [Mishra's \(2016\)](#) models, returned items will only be reworked, and the rest will be disposed of. In this case, the corruption amount in the items will be high, and their model's flexibility will be less than in real conditions.

The recycling stage of the returned items is a benefit of this model. Since recycled items can be used in the production process, manufacturers understand that product recycling can lead to increased profits. Returned items, in addition to manufactured goods, could also be work in process goods. Returned items can be work in process and manufactured items, some of which cannot be recycled and will be disposed of as spoiled items. Returned items may be reworked or recycled. It is assumed that the reproduction and recycling processes are complete, and all inputs have been converted into the desired output. Otherwise, if there is waste in the recycling and reproduction processes, the model will automatically adapt to new coefficients by adjusting its structure.

Compared to previous models, one significant benefit of this model is that the sum of each initial item is sufficient only for production in the next stage. It is a multiplier of the number and the amount of inventory used in the BOM. It prevents the development of surplus inventories.

Since the proposed optimal control model is linear-quadratic, an accurate answer could be obtained. However, approximate approaches can be used for large-scale problems. The state variables' positive values represent surplus inventory, which exceeds the warehouse capacity, and the negative values represent the warehouse capacity that has not been utilized fully. As shown in the figures, the inventories are close to the target values after short times when the order programs are set.

6.2. Practical implications

A three-level BOM model is presented in this study, which also offers the flexibility to produce products with higher BOM levels.

The finite capacity of activities at workstations leads to limitations such as production, reconstruction, and recycling goals. The inventory objective is to minimize the difference between the stock level and its precautionary reserve level. The purpose of disposing of items indicates the desired level of disposal of perishable items, and the capacity to order, release, and transport raw parts are among other goals. Also, in MPS, the target demand for the final product is usually defined as planned demand. Therefore, minimizing the difference between demand and demand target at any given time creates consistency in the production process with the planned demand.

Positive market values are due to the unnecessary release of goods relative to MPS' anticipated market. Similarly, negative values for demand indicate that product release is lower than the planned demand for MPS. However, as shown in the figures, the other variables are set

so that the $\Delta P_{mA}(t)$ converged to zero. It means that demand converges to predetermined target values.

As shown in Figure 4, the changes in the 3D panel inventory have initially increased. Because the difference between the input variables of the sent skeleton levels and foam sent to this inventory has increased from the amount of 3D panel goods seen in figure 5, and then converges to zero. Because the amount of sending 3D panel items deviation from the desired level to the previous level has converged to zero, the difference between the amount of deviation of skeletal and foam items from the desired level of deviation of the final product from the desired level has increased. After the convergence of all three variables to zero, this difference is reduced and converges to zero. Therefore, the final product's increase is due to the over-shipment of two skeletal and foam items. Thus, to converge faster, the company should act as shown in Figure 4, without delay. In the state of delay, as shown in Figure 6, it sends two skeletal and foam goods.

According to Figure 4, the foam inventory rapidly converges to the desired amount. If Figure 2 is taken into account, the foam raw material's deviation level is removed from this inventory. The level of the deviation of the raw material shipment is included. Figure 5 shows that the convergence velocity of sent items is greater than the order variable's convergence velocity. This means that the input rate has decreased relative to the output, resulting in an increase in the variable convergence velocity of the foam inventory mode.

As the input and output variables to the skeleton's inventory deviate from its desired value, all of them are state variables that have been inputted and outputted at a constant rate, so no significant change in the values of this variable has occurred. It is uniformly converged to its target value, which is zero.

The amount of the state variable of the skeletal stock level has increased from the desired predetermined value overtime period $[0, 0.6]$, if Figure 6 is taken into account. Because in this period, the convergence velocity of the control variables and the input state were higher than the convergence velocity of the output variables. However, after this period, the convergence velocity in the output variables has increased, resulting in a decrease in the deviation of the skeletal stock level from its desired value.

Analyzing the variable behavior of the final inventory mode of the product in Figure 6 shows that the inventory amount of this product first decreased and then converged to zero. According to Equation (20) and the coefficients of 3D panel product inventory variable in the matrix B' in "production -inventory Optimal control model of 3D panels considering production lead time"

section, it can be seen the control variables of the fork, mesh, and skeleton order level are the input variables and the order level of the foam. The amount of sent 3D panel is the output ones. Due to the behavior of the above variables in figure 7, the negative value of the order levels of the two raw materials of mesh and fork and their coefficients in the matrix B' , the final product and the order level of the raw material of the foam are converged with delay to their target, which reduces the inventory variable value of the final product in the delayed state. The lack of 3D panel inventory in the mentioned range is due to the high level of ordering of the two raw materials of mesh, fork, and skeleton.

7. Conclusions and future suggestions

A quadratic linear optimal control model is modeled in this paper for a multi-stage production-inventory MRP system, which considers the lead time of production. A delayed dynamic system was deemed for this reason. In the proposed model, the value of the objective function indicates the convergence rate of the variables (state and control functions) to their respective values. The inventories are state variables, while the order variables, the number of shipment goods, and the amount of demand for work in process are control variables. Production lead time refers to the time required to set up and process machines, as well as the time required to transport items between different parts of the system. One of the innovations in the proposed optimal control model compared to previous models is that it provides functions, allowing the amount of items sent to the next stage to be as much as needed for production, thereby preventing surplus inventory.

In the delay model, the optimal delay control problem was approximated to a non-delay problem using the Taylor expansion. Finally, the exact answer to the problem without delay and the approximate answer to the delay problem were calculated and compared. A comparison of these responses revealed that the convergence of the non-delayed response to its target value is faster than that of the delayed one. Although the short lead time is assumed, the value of the delayed state's objective function is greater than the value of the non-delay problem. When the unit of time is large, the production lead time (less than one) can be reasonable. In the numerical simulation section, the time horizon $T = 6$ is considered, the lead time $\tau_A = 0.1$ means 2.4 hours. One of the advantages of the proposed model is that, unlike the existing methods, the production lead time can be continuous and a fraction of a unit of time.

Compared to the previous models, one of the significant advantages of this model is that the sum of each initial item until the next step is sufficient only for production. It is the quantity

factor and quantity of inventory used in the BOM that prevent the development of excess inventory. In this paper, a general material requirement planning (MRP) system with deteriorating items for continuous production processes is considered, and an optimal control model is introduced, taking into account finite capacity constraints. It helps planners consider and model limited capacities during scheduling processes. In the optimal solution, when the state and control variables tend to zero, it means that they converge to the target values of the variables based on the optimal plan. According to Table 1, some existing optimal control models for inventory-production systems were multistage; however, the authors did not consider the quantity of ordered items (raw materials) in the final product. Also, they did not consider any lot-sizing policy. Therefore, our approach for CMRP is new, considers which it deems the BOM by determining the amount of ordered items in the finished product along with the continuous production approach in a continuous time framework, as well as the LFL lot-sizing policy.

The optimal control model, in which the time parameter is continuous, is capable of modeling the state and control variables so that they converge to their target values. Since this research focuses on three-level BOM products, it is recommended that further research be conducted for higher-level BOM products. Additionally, this research considers the Lot for Lot ordering method. In future research, other types of ordering systems could be considered. As a future study, restrictions on control and inventory variables could be considered. In this case, different optimization conditions must be obtained. Uncertainty methods could be used for the proposed model parameters, such as random planning. A closed-loop answer for the proposed system could also be obtained and analyzed. In this study, the values of control variables (order, send, and demand) and state variables (inventories) are calculated as time functions, so the answer is open-loop. That order, shipment, and demand could be calculated as inventory functions (closed-loop). The proposed algorithm could be developed to incorporate other variables of state and control if conditions change. However, when the number of production lead times increases or the number of stages increases, the approximation error also increases. It is because the first period of approximation was used in the development of the Taylor expansion. Other existing mathematical methods could be used to solve the system of delayed differential equations in both cases. Instead of linear relationships, nonlinear relationships between parameters could be used. In this case, the calculated error could also be increased.

Disclosure statement

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References

- AL-Khazraji, H., Cole, C. and Guo, W., 2021. Optimization and simulation of dynamic performance of production–inventory systems with multivariable controls. *Mathematics*, 9(5), p.568. <https://doi.org/10.3390/math9050568>.
- Benkherouf, L., Skouri, K. and Konstantaras, I., 2016. Optimal control of production, remanufacturing and refurbishing activities in a finite planning horizon inventory system. *Journal of Optimization Theory and Applications*, 168(2), pp.677–698. <https://doi.org/10.1007/s10957-015-0741-9>.
- Dhaiban, A.K., 2022. An Integer Optimal Control Model of Production-Inventory System. *Statistics, Optimization & Information Computing*, 10(3), pp.762–774. <https://doi.org/10.19139/soic-2310-5070-747>.
- Dizbin, N.M. and Tan, B., 2020. Optimal control of production-inventory systems with correlated demand inter-arrival and processing times. *International Journal of Production Economics*, 228, p.107692. <https://doi.org/10.1016/j.ijpe.2020.107692>.
- Dong, M., He, F. and Wu, Z., 2011. Optimal control of a continuum model for single-product re-entrant manufacturing systems. *International journal of production research*, 49(21), pp.6363–6385. <https://doi.org/10.1080/00207543.2010.519736>
- ElHafsi, M., Fang, J. and Hamouda, E., 2021. Optimal production and inventory control of multi-class mixed backorder and lost sales demand class models. *European Journal of Operational Research*, 291(1), pp.147–161. <https://doi.org/10.1016/j.ejor.2020.09.009>.
- Foul, A. and Tadj, L., 2007. Optimal control of a hybrid periodic-review production inventory system with disposal. *International Journal of Operational Research*, 2(4), pp.481–494. <https://doi.org/10.1504/IJOR.2007.014175>.
- Gao, Y., 2022. Operator splitting method for the stochastic production–inventory model equation. *Computers & Industrial Engineering*, 174, p.108712. <https://doi.org/10.1016/j.cie.2022.108712>.
- Grubbstrom, R.W. and Tang, O., 2012. The space of solution alternatives in the optimal lotsizing problem for general assembly systems applying MRP theory. *International Journal of Production Economics*, 140(2), pp.765–777.
- Grubbstrom, R.W., Bogataj, M. and Bogataj, L., 2010. Optimal Lotsizing within MRP Theory. *IFAC Proceedings Volumes*, 42(4), pp.15–30. <https://doi.org/10.3182/20090603-3-RU-2001.0562>.
- Hatami-Marbini, A., Sajadi, S.M. and Malekpour, H., 2020. Optimal control and simulation for production planning of network failure-prone manufacturing systems with perishable goods. *Computers & Industrial Engineering*, 146, p.106614. <https://doi.org/10.1016/j.cie.2020.106614>.
- Hedjar, R., Tadj, L. and Abid, C., 2012. Optimal Control of Integrated Production–Forecasting. *Decision Support Systems*, p.117.
- Ignaciuk, P. and Bartoszewicz, A., 2010. Linear–quadratic optimal control strategy for periodic-review inventory systems. *Automatica*, 46(12), pp.1982–1993. <https://doi.org/10.1016/j.automatica.2010.09.010>.

- Ignaciuk, P., 2022. Linear-quadratic optimal control of multi-modal distribution systems with imperfect channels. *International Journal of Production Research*, 60(18), pp.5523-5538. <https://doi.org/10.1080/00207543.2021.1963876>.
- Le Thi, H.A. and Tran, D.Q., 2014. Optimizing a multi-stage production/inventory system by DC programming based approaches. *Computational Optimization and Applications*, 57(2), pp.441-468. <https://doi.org/10.1007/s10589-013-9600-5>.
- Lee, C., Liu, X., Liu, Y. and Zhang, L., 2021. Optimal control of a time-varying double-ended production queueing model. *Stochastic Systems*, 11(2), pp.140-173. <https://doi.org/10.1287/stsy.2019.0066>.
- Louly, M.A., Dolgui, A. and Al-Ahmari, A., 2012. Optimal MRP offsetting for assembly systems with stochastic lead times: POQ policy and service level constraint. *Journal of Intelligent Manufacturing*, 23(6), pp.2485-2495. <https://doi.org/10.1007/s10845-011-0515-7>.
- Luo, Y., Sima, Q., Ji, T., Sun, F., Liu, H. and Zhang, J., 2024, May. Smooth computation without input delay: robust tube-based model predictive control for robot manipulator planning. In *2024 IEEE International Conference on Robotics and Automation (ICRA)* (pp. 10429-10435). IEEE. <https://doi.org/10.1109/ICRA57147.2024.10610952>.
- Megoze Pongha, P., Kibouka, G.R., Kenné, J.P. and Hof, L.A., 2022. Production, maintenance and quality inspection planning of a hybrid manufacturing/remanufacturing system under production rate-dependent deterioration. *The International Journal of Advanced Manufacturing Technology*, 121(1), pp.1289-1314. <https://doi.org/10.1007/s00170-022-09078-3>.
- Mezghiche, A., Moulaï, M. and Tadj, L., 2015. Model predictive control of a forecasting production system with deteriorating items. *International Journal of Operations Research and Information Systems (IJORIS)*, 6(4), pp.19-37. <https://doi.org/10.4018/IJORIS.2015100102>.
- Milne, R.J., Mahapatra, S. and Wang, C.T., 2015. Optimizing planned lead times for enhancing performance of MRP systems. *International Journal of Production Economics*, 167, pp.220-231. <https://doi.org/10.1016/j.ijpe.2015.05.013>.
- Mishra, U., 2016. An EOQ model with time dependent Weibull deterioration, quadratic demand and partial backlogging. *International Journal of Applied and Computational Mathematics*, 2(4), pp.545-563. <https://doi.org/10.1007/s40819-015-0077-z>.
- Nakhaeinejad, M., Khademi Zare, H., Habibi, M. and Khodoomi, M.R., 2023. Improvement of multi-item order systems and inventory management models using optimal control theory. *Transactions of the Institute of Measurement and Control*, 45(1), pp.104-119. <https://doi.org/10.1177/01423312221109724>.
- Öztürk, H., 2021. Optimal production run time for an imperfect production inventory system with rework, random breakdowns and inspection costs. *Operational Research*, 21(1), pp.167-204. <https://doi.org/10.1007/s12351-018-0439-5>.
- Pooya, A. and Pakdaman, M., 2017. Analysing the solution of production-inventory optimal control systems by neural networks. *RAIRO-Operations Research-Recherche Opérationnelle*, 51(3), pp.577-590.
- Pooya, A. and Pakdaman, M., 2018. A delayed optimal control model for multi-stage production-inventory system with production lead times. *The International Journal of Advanced Manufacturing Technology*, 94(1), pp.751-761. <https://doi.org/10.1007/s00170-017-0942-5>.

- Pooya, A. and Pakdaman, M., 2019. Optimal control model for finite capacity continuous MRP with deteriorating items. *Journal of Intelligent Manufacturing*, 30(5), pp.2203-2215. <https://doi.org/10.1007/s10845-017-1383-6>.
- Pooya, A. and Pakdaman, M., 2021. A new continuous time optimal control model for manpower planning with promotion from inside the system. *Operational Research*, 21(1), pp.349-364. <https://doi.org/10.1007/s12351-018-0431-0>.
- Pooya, A., Pakdaman, M. and Tadj, L., 2019. Exact and approximate solution for optimal inventory control of two-stock with reworking and forecasting of demand. *Operational Research*, 19(2), pp.333-346. <https://doi.org/10.1007/s12351-017-0297-6>.
- Rachih, H., Mhada, F. and Chiheb, R., 2022. Simulation optimization of an inventory control model for a reverse logistics system. *Decision Science Letters*, 11(1), pp.43-54.
- Rossi, T., Pozzi, R., Pero, M. and Cigolini, R., 2017. Improving production planning through finite-capacity MRP. *International journal of production research*, 55(2), pp.377-391. <https://doi.org/10.1080/00207543.2016.1177235>.
- Sadeghian, R., 2011. Continuous materials requirements planning (CMRP) approach when order type is lot for lot and safety stock is zero and its applications. *Applied soft computing*, 11(8), pp.5621-5629. <https://doi.org/10.1016/j.asoc.2011.04.002>.
- Shen, J., Jin, Y., Liu, B., Lu, Z. and Chen, X., 2022. An uncertain production-inventory problem with deteriorating items. *Advances in Continuous and Discrete Models*, 2022(1), p.42. <https://doi.org/10.1186/s13662-022-03714-8>.
- Singer, G. and Khmelnitsky, E., 2021. A production-inventory problem with price-sensitive demand. *Applied Mathematical Modelling*, 89, pp.688-699. <https://doi.org/10.1016/j.apm.2020.06.072>.
- Vercraene, S. and Gayon, J.P., 2013. Optimal control of a production-inventory system with product returns. *International Journal of Production Economics*, 142(2), pp.302-310. <https://doi.org/10.1016/j.ijpe.2012.11.012>Get rights and content.
- Yan, S. and Sun, H., 2024. Constrained Optimal Fuel Consumption of HEV: Considering the Observational Perturbation. *arXiv preprint arXiv:2410.20913*. <https://doi.org/10.48550/arXiv.2410.20913>.



A Systematic Review of the Viable System Model: Applications, Insights, and Future Directions

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ABSTRACT

The Viable System Model (VSM) is a foundational framework in organizational cybernetics, designed to manage complexity and ensure systemic viability in dynamic environments. Given the increasing importance of this model in addressing complex organizational challenges, the primary objective of this research is to conduct a comprehensive and systematic review of existing studies in the field of the Viable System Model. This review aims to identify and analyze the practical areas of this model, evaluate its challenges and opportunities in confronting contemporary systemic issues, and extract key insights from 21 peer-reviewed studies. By synthesizing and analyzing the findings of these studies, this paper intends to provide a clear and coherent picture of the Viable System Model's current state and future potential. The process of identifying relevant studies was conducted using the PRISMA method, which involved searching the Scopus database and performing manual searches. This study employs a bibliometric research design, utilizing a quantitative approach and combining bibliometric and network analysis to examine the landscape of VSM research. Key findings highlight VSM's role in enhancing organizational resilience, improving decentralized decision-making, and enabling systemic adaptability. The integration of VSM with emerging technologies—such as artificial intelligence, digital twins, and big data analytics—demonstrates its potential to address contemporary organizational challenges. However, critical gaps remain, including limited empirical validation, insufficient applications in underrepresented sectors such as agriculture and education, and scalability issues for small and medium-sized enterprises (SMEs). The study emphasizes the need for longitudinal research, hybrid frameworks, and sector-specific models to enhance the theoretical and practical utility of VSM. By synthesizing recent applications and identifying research opportunities, this paper reinforces the significance of VSM as a robust approach to managing complexity and outlines pathways for future research.

Keywords

Viable System Model, Systematic Review, Organizational Cybernetics, Complexity Management.

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1. Introduction

The Viable System Model (VSM), developed by Stafford Beer (1972, 1979, 1985), provides a cybernetic framework for understanding and managing organizational complexity. It also offers a theoretical and practical basis for analyzing and managing organizations as complex, self-regulating systems. Beer views organizations as "viable systems" capable of self-organization, self-regulation, and adaptation to changing environments. In this context, he developed the VSM based on a five-level model (System 1 to System 5), where each level (system) plays a distinct role in operational control, coordination, monitoring, strategy, and policy-making. Beer introduced the theoretical foundation of the VSM based on his tripartite approach—Company Brain (1972), Company Heart (1979), and System Diagnosis for Organizations (1985). Beer's work is inspired by cybernetics, particularly Ashby's law of requisite variety (1956), which emphasizes the need for internal complexity within a system to match the complexity of its external environment for survival. Beer's work emphasizes that viable systems, like living organisms, must achieve a balance between autonomy and control while continuously adapting to their environment. This adaptability relies on recursive structures, where each subsystem replicates the overall system's functionality at a smaller scale.

As mentioned, VSM at its core identifies five interconnected subsystems that are essential for ensuring viability (Beer, 1972). System 1 is responsible for the operational units that handle primary activities. System 2 ensures coordination among operational units. On the other hand, System 3 focuses on internal management, overseeing operations, and optimizing resources. Systems 4 and 5 are respectively focused on strategic functions related to environmental analysis, future planning, policy-making, and governance, thereby maintaining the organization's identity and overall coherence. These subsystems interact with each other through continuous feedback loops, enabling organizations to identify and address internal inefficiencies while responding to external pressures (Figure 1).

After Beer, several other scholars have expanded and interpreted the principles of the VSM. For example, Espejo and Harnden (1989) compiled a foundational collection titled "The Viable System Model: Interpretations and Applications," which included case studies and theoretical extensions, and published it as a book. In their work, Spath and Harnden emphasized the adaptability of the VSM to corporate and social systems. Schwaninger (2006) highlighted the diagnostic power of the VSM, describing it as a tool for achieving organizational viability through effective management of complexity. Hoverstadt (2008), in his book "The Fractal Organization," after explaining the concept of fractal systems, suggested that the principles of

the VSM be applied at different levels (micro, meso, and macro) within an organization to address complexities.

On the other hand, [Espinosa and Walker \(2011\)](#) incorporated sustainability concerns into the VSM and expanded its application to address complex ecological and social systems. [Jackson \(2003\)](#), focusing on the role of the VSM as part of broader systems methodologies, emphasized its importance in modern management challenges. The overall conclusion drawn from these studies is that the VSM aligns with the capability for systemic thinking, where organizational elements are viewed as interconnected and dynamic. However, some scholars and researchers held differing opinions regarding the VSM and presented their perspectives within a framework of criticism of the model. For example, [Flood and Jackson \(1991\)](#) noted that although the VSM provides a robust conceptual framework, its implementation can be challenging, particularly in organizations with low systems literacy. From their perspective, the VSM may oversimplify some of the organization's cultural and social dynamics. [Checkland \(1981\)](#) suggested that the abstraction of the VSM makes it difficult for practitioners to translate its principles into practical strategies without significant expertise. Despite the weaknesses noted by some authors, the application of the VSM has been important, and its use has expanded across various fields. Notable applications of the VSM in various areas of an organization include diagnosing organizational issues, streamlining operations, and managing complexity, such as organizational design and restructuring. In this context, [Leonard \(2009\)](#) demonstrated the VSM's ability to identify inefficiencies in organizational structures and enhance coherence between operational and strategic levels. The public sector and governance represent another critical area for using the VSM model. According to [Espinosa et al. \(2007\)](#), who applied the principles of the VSM to public sector organizations, they argued that this model provides a strong framework for improving decision-making and aligning policies in large and complex institutions. Another application of the VSM is its role in knowledge management. One of the key studies in this area is by [Hildreth and Kimble \(2004\)](#), who used the VSM to analyze knowledge networks and communities of practice. These two researchers also emphasized the VSM's ability to enhance innovation and knowledge flow. Sustainability and complexity management can be introduced as one of the new areas that highlight the significance of the VSM application. For a deeper understanding, one can refer to the study by [Espinosa et al. \(2007\)](#). These authors expanded the VSM to address sustainability challenges by managing environmental and organizational complexity. Beer himself implemented the VSM in various

industries, particularly in the "Cybersyn" project in Chile during the 1970s, which aimed to create a real-time cybernetic control system for managing the national economy.

The increasing speed of globalization, technological advancements, and interconnected systems have brought an unprecedented level of complexity to organizations worldwide. As modern challenges such as globalization, digital transformation, and sustainability rise, there has been a renewed interest in the VSM, highlighting the growing need for robust and systemic approaches to maintain organizational efficiency and flexibility. As [Hoverstadt \(2008\)](#) argued, organizations must adopt the principles of the VSM to sustain agility and adaptability in more complex environments. [Espinosa and Walker \(2011\)](#) examined the impact of using the VSM to address systemic issues in areas such as environmental sustainability and large-scale governance, introducing it as a tool for tackling global complexity. Furthermore, the VSM has also been applied in digital transformation, helping organizations align their operational processes with strategic goals in dynamic and technology-driven environments. Therefore, this study provides a comprehensive overview of previous research on the VSM by focusing on its applications, implications, and prospects. This paper aims to systematically review the VSM literature, examining its contributions, limitations, and opportunities for future research. By synthesizing evidence from diverse domains, the review seeks to answer the following questions:

QR1: In what domains has the Viable System Model been applied?

QR2: What insights have emerged from these applications?

QR3: What challenges and opportunities exist for the VSM in addressing contemporary systemic issues?

2. Materials and methods

2.1. Research design

This study adopts a systematic review approach, adhering to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The PRISMA flow diagram plays a crucial role in ensuring the transparency, rigor, and replicability of systematic reviews. By visually summarizing each phase of the study selection process, the flow diagram allows readers to assess the methodology and validate the comprehensiveness of the evaluation. It aligns with internationally recognized standards for systematic reviews, such as those established by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses. The inclusion of the PRISMA diagram ensures that the study selection process adheres to systematic review standards, fostering greater confidence in the validity and reproducibility of the findings

(Moher et al., 2009). Therefore, this study evaluates the existing literature using a PRISMA-based structured methodology to highlight the enduring significance of VSM, identify research gaps, and propose future opportunities to advance the application of the model in a complex and digital world. This diagram includes four stages: identification, screening, eligibility, and inclusion (Tugwell and Tovey, 2021).

- *Identification*: This phase includes locating records through database searches (e.g., Scopus) and manual reference checks, ensuring comprehensive coverage of relevant literature.
- *Screening*: During this phase, duplicate records are removed, and the remaining studies undergo a title and abstract review to exclude irrelevant publications.
- *Eligibility*: Full-text articles that pass the screening phase are assessed against the predefined inclusion and exclusion criteria to determine their suitability for inclusion.
- *Inclusion*: This final stage identifies the studies that meet all criteria and are included in the qualitative synthesis.

By breaking down the study selection process into these stages, the PRISMA diagram enhances transparency, clarity, and replicability, ensuring that the review aligns with internationally recognized standards for systematic reviews (Figure 2). The Scopus database was the primary data source due to its comprehensive coverage of high-impact journals. It was supplemented by manual reference checks to capture seminal studies that might not be indexed within the primary database, ensuring completeness and credibility. A standardized data extraction framework was used to enhance methodological reliability, categorizing information into application domains, methodologies, key findings, limitations, and future research directions. To maintain reliability, a double-screening process was implemented to validate article selection, and researchers performed inter-coder reliability checks to minimize subjective bias. Validity was reinforced by including only peer-reviewed studies. Since this study is based entirely on secondary data, ethical concerns were minimal. Yet, academic integrity was upheld by ensuring proper citation of sources, methodological transparency, and the avoidance of selective reporting.

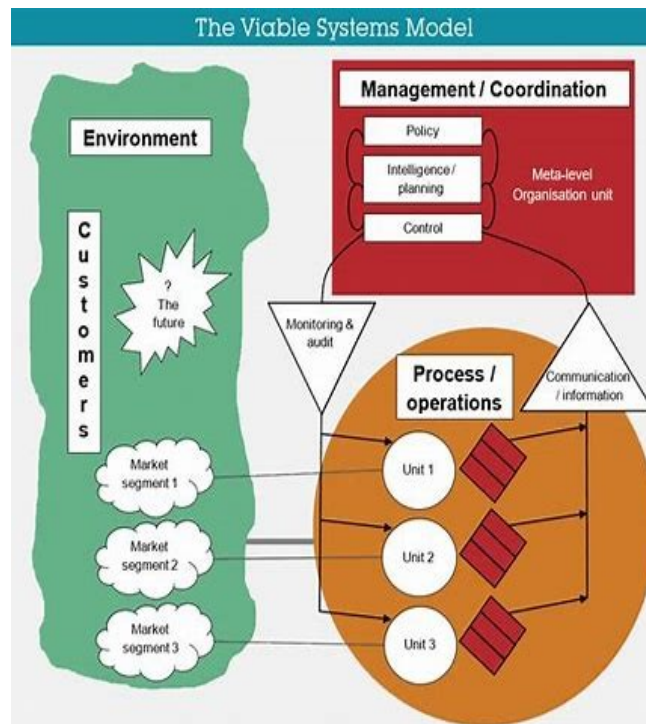


Figure 1. Structure and components of the VSM model (Beer, 1972)

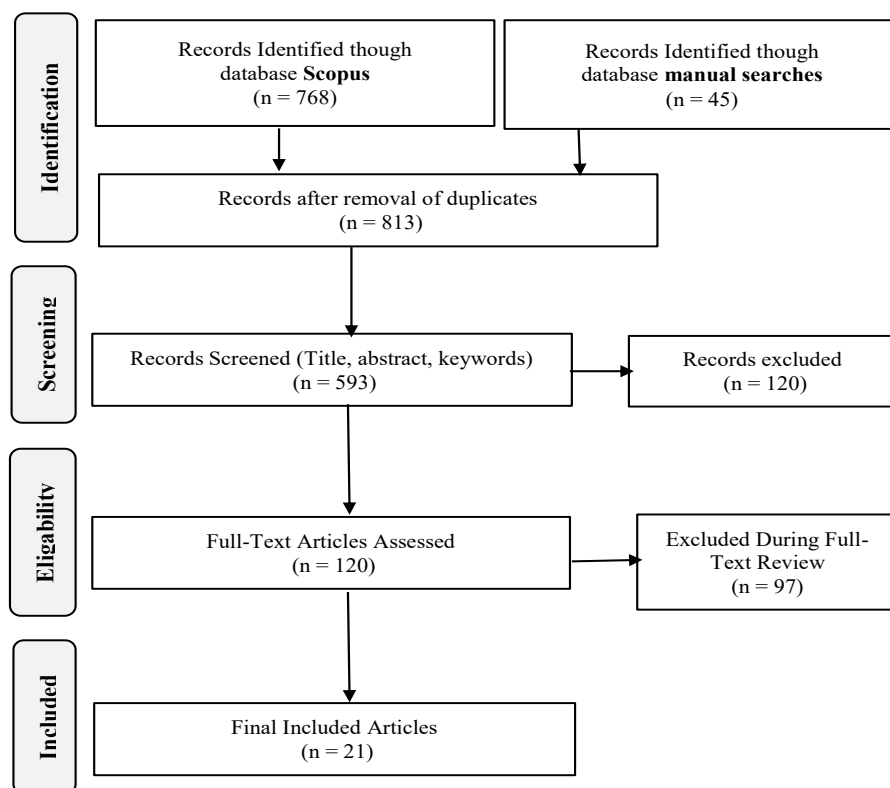


Figure 2. Process of selecting and screening articles

This study employs a bibliometric research design, utilizing a quantitative approach and combining bibliometric and network analysis to examine the landscape of VSM research. This methodology integrates descriptive bibliometric analysis, co-occurrence keyword analysis, and network clustering, ensuring a systematic and data-driven approach to identifying research trends, influential authors, and conceptual structures. In this regard, a purposive sampling technique was used, and relevant studies were selected from the Scopus database, complemented by a manual review of sources to ensure comprehensive coverage of key contributions. The dataset comprises 768 documents from 378 sources, encompassing a diverse and interdisciplinary research area. Data collection tools included the R Bibliometrix package for bibliometric analysis, which generated co-occurrence networks and thematic maps. The PRISMA framework structured the identification, screening, eligibility, and inclusion of studies, ensuring transparency and reproducibility. Standard data cleaning and preprocessing techniques were applied to guarantee reliability and validity, and duplicate cases and irrelevant publications were removed. Reliability checks among coders were conducted to classify and interpret keyword clusters, thereby minimizing bias and ensuring accuracy. Using Bradford's law and co-occurrence analysis further validated the robustness of the methodology. Ethically, this study is based entirely on secondary data, eliminating concerns about human participants, privacy, and consent. Scientific integrity was maintained through proper citation, transparent reporting, and adherence to bibliometric standards.

2.2. Search strategy

A comprehensive literature search was conducted using the Scopus database, supplemented by manual reference checks to identify additional relevant studies. The search query was designed to encompass the broad applications of VSM:

(“Viable System Model” OR (“cybernetics” AND (“systemic approach” OR “organizational theory” OR “organizational management”))).

The inclusion of manual searches was deemed essential to ensure comprehensive coverage, as certain relevant studies may not be indexed in Scopus or could be missed due to variations in indexing terms. Manual searches also provided an opportunity to identify references from key articles, ensuring no significant contributions were overlooked. Additionally, to ensure effective communication and quality, the entry and exit criteria were applied as outlined in [Table 1](#).

2.3. Data extraction and synthesis

A systematic and detailed data extraction process was applied to the 21 selected studies. A standardized extraction form was used to ensure consistency and completeness of the extracted information. The categories documented for each article, as shown in Figure 3, include: authors and year, application area, research focus, methodology, key findings, gaps and challenges, and future research directions.

The extracted data were synthesized using thematic analysis, which involved identifying patterns and grouping insights under relevant themes such as applications, challenges, and emerging opportunities.

Table 1. Entry and exit criteria in the context of searching for relevant scientific resources on vsm

Inclusion Criteria	- Studies that focus on the theoretical or practical applications of the Viable System Model (VSM). - Articles published in peer-reviewed journals. - Studies addressing organizational complexity, systemic approaches, or management challenges. - Articles published in English.
Exclusion Criteria	- Non-peer-reviewed articles, including editorials, book reviews, and opinion pieces. - Papers lacking empirical evidence or practical applications. - Duplicate studies were identified across sources. - Studies unrelated to VSM or its core principles.

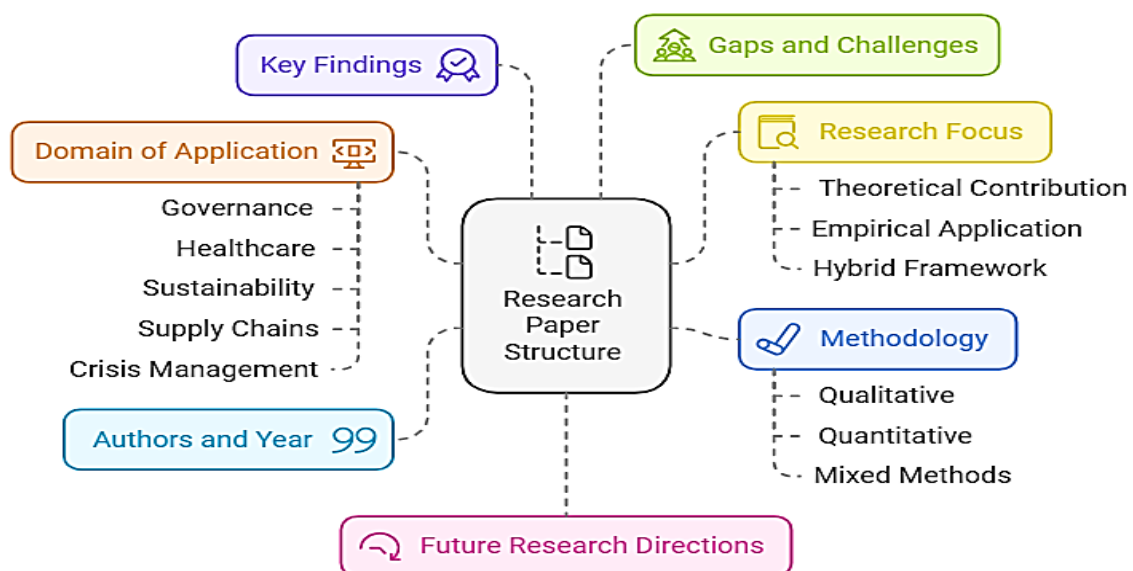


Figure 3. Selected categories for each article

3. Results

The research results are presented in a structured format, utilizing tables, diagrams, and images to ensure clarity and comprehensibility. All visuals are clear and easy to interpret, and they include appropriate axes labels, captions, and references to the text. As mentioned in the previous section, a total of 21 articles were selected for a systematic review of the literature on VSM. Reviewing these studies indicates that the application areas of the VSM model are extensive. However, the six main areas of application for this model are governance, healthcare resilience, sustainability, supply chain optimization, crisis management, and technology integration (Table 2).

Chan (2011) explores organizational resilience in a small Hong Kong garment company by integrating the Viable System Model and Multi-Criteria Decision Analysis (MCDA) as a systematic decision-support tool. VSM diagnoses cybernetic weaknesses by assessing key organizational subsystems—operations, coordination, control, auditing, intelligence, and policy—identifying critical gaps in autonomy-control balance, internal coordination, and lack of auditing mechanisms. To address these vulnerabilities, MCDA, using the Superiority and Inferiority Ranking (SIR) method, is applied to evaluate four alternative structural arrangements based on corporate credibility and autonomy-control trade-offs. The findings indicate that outsourcing non-core functions such as quality control, shipping, and production enhances resilience by improving financial stability and stakeholder trust, despite leading to lower profit margins. A post-implementation evaluation over 15 months reveals increased adaptability, expanded product lines, and sustained client relationships. It confirms that the VSM-MCDA integration is a robust, data-driven framework to guide SMEs in strategic decision-making, organizational restructuring, and resilience-building in volatile business environments.

The study by Spyridopoulos et al. (2014) proposes a holistic cyber assurance framework for protecting critical infrastructure by integrating the VSM into cybersecurity risk assessments for Industrial Control Systems (ICSs), specifically Supervisory Control and Data Acquisition (SCADA) systems. Traditional risk management approaches often fail to address the systemic interdependencies, emerging cyber threats, and resilience needs of ICSs, necessitating a shift towards a system-of-systems perspective. The methodology applies VSM's cybernetic principles to model ICSs as hierarchical, self-regulating systems, identifying cyber assets, internal and external interactions, threats, and vulnerabilities through a recursive assessment process. The risk assessment framework categorizes threats affecting system viability, including Denial-of-Service attacks, data corruption, and unauthorized access. It maps them

across VSM's five subsystems: operations, coordination, control, strategic intelligence, and policy. The results demonstrate that VSM enhances cyber risk visibility, enables structured threat modeling, and fosters resilience by addressing technical and organizational cybersecurity gaps. The study concludes that VSM is a powerful diagnostic tool for critical infrastructure cyber assurance, offering a systemic, adaptive, and scalable approach to managing cyber risks across multiple organizational levels.

Espinosa et al. (2015) develop a systemic methodology for supporting strategy implementation in a Latin American multinational by integrating the VSM with a soft OR (Operational Research) approach to address the "implementation gap"—the challenge of aligning organizational structures with strategic goals. The study uses an action research methodology to enhance the "Methodology for Organisational Self-Transformation," incorporating mixed methods, including quantitative surveys, qualitative interviews, and participatory workshops. The VSM framework diagnoses structural weaknesses at different organizational levels, mapping complexity through five systemic functions (operations, coordination, control, intelligence, and policy). Findings reveal critical issues in decentralization, decision-making bottlenecks, and a lack of coordination mechanisms, particularly between corporate headquarters and regional branches. A structured redesign proposal emerges, striking a balance between autonomy and control by establishing collegiate decision-making bodies, innovation units, and decentralized accountability mechanisms. The results demonstrate that VSM enhances organizational learning and decision-making, fostering systemic adaptability, stakeholder engagement, and strategic alignment.

Panagiotakopoulos et al. (2016) examine the integration of sustainability management within organizations by applying the VSM to bridge the gap between adopting sustainability standards and their practical implementation. Focusing on the ISO 26000 Social Responsibility (SR) standard, the research employs a conceptual modeling approach using the hypothetical Widget Co. to illustrate how VSM can map sustainability functions across organizational governance systems. The VSM framework systematically aligns ISO 26000 clauses with the five core subsystems—operations, coordination, control, intelligence, and policy—to identify critical challenges in embedding sustainability into daily operations. The findings demonstrate that VSM clarifies SR responsibilities, enhances dynamic interrelations among governance structures, and facilitates a systemic approach to sustainability integration. The study highlights VSM's potential to serve as a strategic tool for organizational transformation, providing a structured method to align corporate governance, stakeholder engagement, and sustainability initiatives into a cohesive management framework.

Vahidi and Aliahmadi (2019) develop a multi-methodological approach that integrates the VSM with System Dynamics (SD) to enhance complexity management and decision-making within organizations, addressing the limitations of single-method frameworks. Traditional non-systemic management approaches often fail to tackle organizational complexity and adaptability, which requires holistic, dynamic methodologies. The research constructs a dynamic model that fuses VSM's cybernetic structure—focusing on autonomy, control, coordination, and viability—with SD's feedback loops, stock-flow structures, and simulation capabilities. It enables organizations to visualize systemic interdependencies and simulate the impact of decisions over time. Using a case study in a management consulting firm, the study demonstrates that the proposed model enhances problem-solving efficiency, knowledge management, and resilience to environmental changes. Results indicate that the integration of VSM and SD compensates for the weaknesses of each method individually, providing a structured yet adaptive approach to handling organizational complexity.

Gallego-García et al. (2019) present an integrated capacity management model for an automotive manufacturing plant, leveraging VSM and Digital Twin simulation to enhance decision-making in demand-driven production systems. The research addresses the challenge of matching supply capacity with fluctuating customer demand, proposing a systemic framework that combines cybernetic principles of VSM with real-time digital twin simulations for capacity adjustments. Using a case study approach, the methodology constructs a recursive VSM-based decision-making structure, enabling autonomous capacity adjustments based on real-time demand forecasting, production constraints, and investment decisions. A simulation model replicating different demand scenarios tests the reactivity, flexibility, and economic impact of decision-making strategies. The findings demonstrate that VSM-enabled capacity management reduces decision-making delays, enhances production efficiency, and minimizes financial risks through adaptive planning mechanisms, outperforming traditional static approaches. The research highlights the effectiveness of VSM-Digital Twin integration in creating a resilient, self-regulating production system, advocating for its adoption in high-variability industries to optimize operational responsiveness, cost efficiency, and long-term viability.

Cardoso Castro and Espinosa (2020) explore the integration of Social Network Analysis (SNA) with the VSM as a methodological advancement for diagnosing organizational pathologies, addressing limitations in existing VSM-based diagnostics. The research employs an action research approach within a European eco-community, using VSM to map systemic

functions (operations, coordination, control, intelligence, and policy) and SNA to analyze communication networks through centrality measures, connectivity structures, and information flow patterns. The results identify critical organizational dysfunctions, including weak decision-making hierarchies, fragmented coordination mechanisms, and communication bottlenecks, highlighting the misalignment between formal governance structures and informal influence networks. The study finds that integrating SNA enhances VSM diagnostics by offering a quantitative measure of interaction patterns, enabling the detection of hidden power structures, weak communication channels, and decision-making inefficiencies. The research contributes to organizational cybernetics and complexity management by demonstrating how VSM-SNA integration provides a robust framework for structural analysis, strategic reconfiguration, and resilience building, offering a novel, systemic, data-driven approach to diagnosing and mitigating organizational dysfunctions in complex, self-organizing systems.

[Lowe et al. \(2020\)](#) examine the difficulties of applying the VSM in practice and propose a set of constitutive rules to guide its implementation, ensuring theoretical rigor while allowing for flexibility in adapting to various organizational contexts. Recognizing that VSM's complexity often hinders its accessibility for practitioners, the authors develop a Hierarchical Process Model (HPM) to structure VSM engagements systematically. The research employs a cross-case analysis of three VSM interventions—in the UK Ministry of Defence, an Irish Ecovillage, and a Latin American Corporation—to examine how practitioners adapt VSM in diverse settings while maintaining methodological integrity. Using a performative epistemology, the study identifies key principles for VSM practice, including balancing problem structuring with systemic diagnosis, aligning interventions with organizational needs, and ensuring participatory engagement. Findings demonstrate that VSM remains a robust organizational design and resilience tool, but its application requires structured guidance to maintain conceptual fidelity.

[Adham et al. \(2020\)](#) apply the VSM to diagnose the halal industry in Taiwan, a Muslim-minority country aiming to integrate into the global halal market. Using qualitative research methods, including in-depth interviews with certification agencies, halal business owners, and consumers, as well as observations and online reviews, the study maps Taiwan's halal industry ecosystem onto the VSM framework. Findings indicate that while Taiwan has established multiple halal certification bodies and a supportive trade promotion unit (the Taiwan Halal Center), it lacks a formal halal industry development policy, resulting in the absence of key systemic functions, such as policy formulation, intelligence gathering, and coordination. The study highlights the central role of locally born Muslims and mosques in facilitating halal

certification, while also identifying fragmented governance, limited domestic awareness of the halal market, and inadequate international branding as challenges. Recognition from Malaysian authorities is deemed crucial for Taiwanese halal products to gain global market acceptance.

[Pollock and Steen \(2021\)](#) examine the Total Defence System (TDS) of Norway and the UK in the context of the COVID-19 crisis, using the Viable System Model (VSM) to assess its resilience and effectiveness. TDS is a civil-military cooperation framework designed to enhance national crisis response by integrating government agencies, military forces, health services, and private sector actors. The research employs a comparative case study approach, utilizing policy document analysis, media reports, and crisis response evaluations to assess the viability of TDS across five systemic functions: anticipation and monitoring, leadership and decision-making, collaboration and joint effort, coordination structure, and crisis communication. Findings reveal critical governance pathologies in both countries, including coordination inefficiencies, leadership inconsistencies, and communication failures, particularly in the UK's fragmented crisis response system. Norway's centralized and collaborative approach resulted in swift decision-making, higher public trust, and stronger resilience. In contrast, the UK's delayed lockdown, conflicting crisis messaging, and limited inter-agency cooperation led to higher mortality rates and public distrust.

[Alves et al. \(2021\)](#) employ the VSM to diagnose the development of fish farming policy in Tocantins, Brazil, assessing its systemic structure, governance, and operational challenges. The research follows a multi-stage systemic analysis, beginning with the identification of organizational identity and policy objectives, followed by the unfolding of vertical and horizontal complexity to examine how policy functions are structured across different governance levels. Using TASCOI analysis (Transformation, Actors, Suppliers, Customers, Owners, Interveners) and software-assisted VSM modeling, the study identifies key systemic weaknesses, including poor coordination, fragmented regulatory mechanisms, and inefficient decision-making structures within the State Fish Farming Development Council (CONDEPISCI). Findings reveal gaps in systemic integration, characterized by unclear governance roles, inadequate enforcement mechanisms, and insufficient stakeholder collaboration, which hinder the effective execution of policies and the growth of the industry. The study highlights the importance of structured governance, cross-sector collaboration, and adaptive policy mechanisms in enhancing the viability of fish farming as a strategic economic activity. It concludes that VSM provides a robust framework for diagnosing policy failures and designing governance reforms, advocating for institutional restructuring, digital governance

integration, and participatory decision-making to ensure sustainable aquaculture development in Brazil.

[Espejo \(2021\)](#) extends the Viable System Model (VSM) by introducing the Enterprise Complexity Model (ECM) as a methodological framework for managing complexity in emerging organizational forms, particularly in highly interconnected and dynamic environments. Traditional VSM approaches focus on the viability of individual enterprises, whereas the ECM conceptualizes organizational networks as adaptive, collaborative systems that integrate multiple enterprises, digital technologies, and sustainability imperatives. Using the Viplan Methodology, the study examines how enterprises navigate complex ecological, social, and economic demands by structuring self-regulating systems that enhance resilience, autonomy, and coordination. Findings indicate that enterprises facing rapid environmental changes require distributed governance models, reflexive learning loops, and algorithmic decision-making tools to maintain systemic viability. The ECM facilitates reconfigurable organizational structures that align with real-time data analytics, artificial intelligence, and decentralized resource management, fostering continuous innovation and strategic adaptation.

[Adham et al. \(2022\)](#) employ the VSM as a diagnostic framework to analyze the evolution and viability of the Malaysian halal certification system, a globally recognized standard ensuring compliance with Islamic dietary laws. Using a qualitative research methodology, the study conducted in-depth interviews with 20 executives from key institutions involved in halal certification, alongside document analysis tracing policy development from the 1970s to 2020. Findings reveal that the system's development followed a staged progression, driven by crises and institutional responses, evolving from an unstructured, state-based approach to a centralized, highly regulated system under the Department of Islamic Development Malaysia (JAKIM). Systemic weaknesses were identified in policy integration, enforcement mechanisms, inter-agency coordination, and industry engagement, resulting in inconsistencies in governance and a lack of international recognition. The research highlights the necessity of adaptive governance, digital traceability, and stronger regulatory frameworks to enhance the system's viability and effectiveness. By integrating policy evolution with the principles of systemic viability, the study provides a blueprint for strengthening halal industry ecosystems, advocating for strategic alignment, cross-sector collaboration, and international standardization to sustain Malaysia's leadership in the global halal economy.

Rodriguez-Ulloa (2022) presents a systemic approach to reforming Peru's governance, utilizing Stafford Beer's VSM to address its structural inefficiencies, bureaucratic rigidity, corruption, and lack of strategic foresight. By diagnosing Peru's governance across four key

perspectives—sectoral (government functions), regional (territorial administration), river basins (environmental sustainability), and macroregional (integrated national development)—the research illustrates how a cybernetic governance framework can enhance adaptability, efficiency, and resilience. The methodology employs VSM in two modes: Diagnosis Mode, which identifies Peru's governance dysfunctions, and Design Mode, which proposes a cybernetic transformation leveraging real-time data integration, process automation, and intelligent decision-support systems. The study integrates systemic methodologies, including soft systems methodology (SSM), business process management (BPM), dynamically balanced scorecards, agent-based modeling (ABM), and social network analysis (SNA), to enhance the management of governance complexity. Findings indicate that Peru's governance must transition from a hierarchical, reactive model to a cybernetic, process-oriented system, emphasizing real-time monitoring, automation, and strategic adaptability. The proposed cybernetic governance model advocates for state reform through process automation (robotic process automation, AI-powered chatbots, and expert systems), intelligent policy execution (utilizing real-time dashboards and data-driven decision-making), and increased funding for science, technology, and innovation (ST&I) to enhance Peru's technological and economic resilience. Additionally, decentralized governance frameworks focused on regional and river basin-based policy execution are recommended to improve localized adaptability. This pioneering application of VSM to national governance provides a blueprint for resilient, technology-driven governance transformation, making it highly relevant for other developing nations seeking systemic reforms in the digital era.

[Adamides et al. \(2023\)](#) present a cybernetic approach to addressing the challenges of municipal waste management by utilizing Stafford Beer's VSM and the VIPLAN methodology to design a more adaptable and resilient waste management organization. The research highlights the increasing complexity of municipal waste management systems (MWMS), driven by evolving consumption patterns, climate change, new waste-processing technologies, and socio-technical transformations, which demand greater organizational flexibility and systemic resilience. Using the Municipality of Patras in Greece as a reference case, the study applies the VSM framework to diagnose inefficiencies and redesign municipal waste governance for enhanced adaptability and sustainability. The methodology follows a structured, three-phase approach: (1) Defining the system's identity and stakeholders through the TASCOI framework, (2) Unfolding organizational complexity by identifying primary waste management activities, regulatory functions, and decision-making structures, and (3) Testing the viability of

the redesigned system through simulated scenarios that evaluate its response to environmental disturbances. The findings reveal rigidities in current municipal waste governance, particularly in resource allocation, decision-making, and environmental scanning, which hinder responsiveness to unforeseen disruptions such as pandemics or changes in waste composition. To enhance resilience, the proposed VSM-based organizational model redistributes decision-making power across five interconnected cybernetic systems: System 1 (operational waste collection and disposal), System 2 (coordination mechanisms), System 3 (resource allocation and performance monitoring), System 4 (environmental scanning and innovation), and System 5 (policy and strategic oversight). The study concludes that a decentralized, recursive structure—where municipal waste units operate autonomously yet interdependently—ensures greater flexibility, efficiency, and integration into a circular economy model. The proposed model demonstrates practical applicability by integrating advanced waste management technologies, predictive analytics, and participatory governance mechanisms, offering a scalable framework for municipalities worldwide seeking to enhance sustainability and resilience in urban waste management.

[Adamides et al. \(2023\)](#) present a systemic cybernetic framework to enhance the resilience of oil refineries against climate-induced disruptions, utilizing Stafford Beer's VSM. Given the increasing vulnerability of critical oil infrastructure to extreme weather events—such as heatwaves, storms, flooding, and wildfires—this research develops a Viable Climate Resilience Providing Organisation (CRPO) to ensure uninterrupted operations and adaptive capacity within a Greek oil refinery. The methodology is based on an action research approach, employing the VIPLAN method to diagnose, design, and test a distributed resilience-providing organizational model. The research follows a three-phase process: (1) Defining the refinery's resilience identity and stakeholders using the TASCOI framework, (2) Mapping organizational complexity by identifying climate vulnerabilities, operational interdependencies, and decision-making structures, and (3) Designing a cybernetic governance model using VSM to distribute resilience-related functions across five systemic levels—System 1 (operational resilience implementation), System 2 (coordination of resilience activities), System 3 (resource allocation and performance monitoring), System 4 (climate foresight and strategic adaptation), and System 5 (policy and governance oversight). Findings reveal that existing refinery resilience strategies are reactive, safety-centric, and fragmented, lacking real-time environmental scanning, decentralized decision-making, and adaptive recovery mechanisms. The proposed CRPO model integrates climate scenario analysis, predictive risk assessments, knowledge-based decision-making, and distributed resilience responsibilities across refinery units, ensuring proactive

adaptation, rapid recovery, and integration of sustainability. This cybernetic resilience framework provides a scalable and transferable model for climate-proofing industrial infrastructures, making a significant contribution to organizational cybernetics, climate resilience governance, and risk-adaptive industrial management.

[Perko \(2023\)](#) presents a systemic and cybernetic examination of data-sharing frameworks, addressing the ethical, social, and governance concerns surrounding current data collection practices, which are predominantly centralized and controlled by data scientists, corporations, and AI developers. The research explores an alternative data-sharing model that grants data producers ownership and governance rights over their data, allowing for a more transparent, ethical, and participatory digital ecosystem. The methodology employs a conceptual and theoretical approach, utilizing literature analysis, system dynamics modeling, and the VSM to assess the viability of a decentralized data-sharing ecosystem. The study contrasts the dominant centralized data collection paradigm—where biometric and behavioral data are amassed in large-scale data lakes for AI-driven analysis—with a proposed data-sharing model in which data producers maintain control, negotiate sharing conditions, and leverage AI-driven agents for intelligent governance. Findings suggest that transitioning from passive data collection to active data governance would significantly enhance transparency, security, and ethical accountability, thereby mitigating risks such as data misuse, exploitation, and privacy violations. The study also reveals technical and structural challenges, including the need for distributed storage, intelligent negotiation protocols, and trust-based regulatory mechanisms. By applying VSM, the research diagnoses the systemic feasibility of this transition, outlining the functional requirements for a resilient, participatory, and AI-enhanced data governance framework.

[Espinosa et al. \(2023\)](#) explore how the VSM and the Self-Transformation Methodology (STM) can be applied to enhance organizational resilience within public healthcare systems. Amidst the challenges posed by the global pandemic, economic instability, and resource constraints, the research focuses on a case study within an English Local Health Trust's (ELHT) Breast Care Unit (BCU), diagnosing systemic inefficiencies and designing a more resilient, adaptable operational structure. The methodology employs a participatory action research approach, utilizing VSM as a diagnostic tool to evaluate the effectiveness of organizational structures and decision-making mechanisms. The study is structured into three key phases: (1) Boundary critique and stakeholder mapping, which defines the system's identity and constraints; (2) VSM-based diagnosis, which identifies governance weaknesses, decision-

making bottlenecks, and operational inefficiencies across five cybernetic levels—System 1 (clinical operations), System 2 (coordination mechanisms), System 3 (performance management), System 4 (innovation and environmental scanning), and System 5 (strategic oversight); and (3) Implementation of self-transformation initiatives, co-designed with participants to address key organizational vulnerabilities. The findings highlight that excessive centralization, rigid financial controls, and a lack of local autonomy hinder real-time responsiveness and adaptive learning within the healthcare unit. The proposed self-transformation interventions emphasize greater decision-making autonomy for clinical teams, a restructured performance management system that prioritizes patient-centric indicators, improved resource allocation processes, and a shift toward a culture of participatory innovation. The study concludes that decentralized governance, empowered frontline staff, and real-time decision-support systems are critical to enhancing resilience and sustainability in public health organizations.

Steen (2024) investigates the role of inter-organizational collaboration in enhancing the viability of disaster response systems by applying Stafford Beer's VSM to analyze the 2020 Gjerdrum landslide crisis response in Norway. The research highlights the impact of effective communication, coordination, and decision-making processes on the resilience and adaptability of emergency response efforts, particularly in disasters induced by climate change. Using a qualitative research design, the study employs document analysis, semi-structured interviews, and thematic analysis to systematically diagnose the structural, communicational, and functional inefficiencies within the Norwegian Search and Rescue (SAR) system. The findings highlight key pathological issues that hinder effective disaster response, including imbalances between centralized and decentralized decision-making, communication breakdowns, inefficient resource allocation, and unclear role distribution among emergency responders. Specifically, the study reveals that while collaboration among police, fire brigades, medical services, and voluntary organizations was essentially practical, the lack of clear leadership transitions, inadequate infrastructure for crisis coordination, and inconsistent information-sharing mechanisms created significant challenges. By applying the VSM framework, the research identifies systemic dysfunctions across five organizational levels—System 1 (operational response), System 2 (coordination), System 3 (resource allocation and performance monitoring), System 4 (environmental scanning and strategic foresight), and System 5 (policy and governance oversight)—and provides targeted recommendations to improve the resilience, efficiency, and long-term adaptability of disaster response networks. The study highlights the

significance of pre-existing inter-organizational relationships, trust-based communication protocols, and dynamic role allocation in establishing a robust crisis management system.

[Perko et al. \(2024\)](#) present a systemic approach to sustainable supply chain (SSC) management, integrating systems thinking, stakeholder theory, and the VSM to create a holistic framework for sustainability. Given the increasing global pressure for responsible and ethical business practices, the research highlights the complex interdependencies between supply chain (SC) members and their economic, social, and environmental contexts, emphasizing the necessity for a holistic approach in sustainability strategies. The methodology employs a structured, conceptual, and empirical approach, combining system dynamics modeling and VSM diagnosis to analyze the systemic viability of SSCs. The research develops two models: (1) a basic holistic model that integrates sustainability as an embedded goal within SC operations and (2) a requisite holistic SSC model that extends sustainability beyond SC members to include regulatory bodies, societal stakeholders, and environmental frameworks. Findings indicate that low-tier SC members, such as suppliers and small-scale producers, lack the autonomy and capacity to engage in sustainability-driven decision-making, necessitating external support mechanisms from regulatory frameworks, incentive structures, and policy reforms. The study also reveals systemic pathologies within SC structures, including profit-driven incentives that conflict with long-term sustainability goals, inefficient regulatory adaptation, and a lack of real-time feedback mechanisms from environmental and societal actors. By applying VSM analysis across five systemic levels—System 1 (operations), System 2 (coordination), System 3 (resource management and performance control), System 4 (strategic foresight and environmental scanning), and System 5 (policy and governance oversight)—the study proposes structural changes that ensure adaptive, resilient, and ethically responsible SC operations.

[Sydelko et al. \(2024\)](#) explore a systemic and participatory approach to enhancing interagency collaboration in tackling wicked problems using Stafford Beer's VSM. Wicked problems, such as international organized crime and its intersection with local gang activity, are highly complex, interdependent, and resistant to traditional reductionist problem-solving methods. The research presents an innovative board game-based application of the VSM designed to facilitate interagency learning, trust-building, and collaborative organizational design. By applying the VSM framework within a game-based intervention, the study demonstrates how agencies can overcome siloed decision-making, interdepartmental rivalries, and inefficient coordination structures, which often hinder responses to large-scale, multi-stakeholder crises. The

methodology follows a systemic intervention approach, integrating boundary critique, systemic perspective mapping, and a facilitated VSM board game workshop to co-design an interagency meta-organization (BlueNet). The research is structured into three key phases: (1) stakeholder mapping and boundary critique, where participants identify the structural barriers to collaboration; (2) systemic perspective mapping, which helps agencies build a shared understanding of interdependencies and overlapping responsibilities; and (3) deployment of the VSM board game, where participants simulate and negotiate the design of an adaptive, cybernetic interagency structure. Findings indicate that pre-existing interagency collaboration is often informal and reliant on personal networks ('I know a guy' approach), leading to inefficiencies in intelligence-sharing, decision-making, and coordinated resource allocation. By structuring BlueNet's organizational design across VSM's five systemic levels—System 1 (operational units), System 2 (coordinating functions), System 3 (resource management and performance oversight), System 4 (strategic foresight and environmental scanning), and System 5 (policy and governance oversight)—the study demonstrates that interagency responses to wicked problems can be optimized through recursive, self-organizing governance structures that enhance adaptability, resilience, and information flow.

Table 2. Key trends across the 21 studies

key trends	Explanations
Governance Applications	- VSM enhances decentralized decision-making by identifying systemic inefficiencies and improving hierarchical communication (Lowe et al., 2020; Espinosa et al., 2023). - Applied to national and local government systems to optimize policy implementation and coordination (Rodriguez-Ulloa, 2022).
Healthcare Resilience	- VSM strengthens resource allocation, emergency response, and resilience in healthcare systems, particularly during crises like the COVID-19 pandemic (Espinosa et al., 2023; Gallego-García et al., 2019). - Improves coordination between departments to maintain operational stability under pressure (Pollock and Steen, 2021).
Sustainability	- VSM aligns organizational processes with sustainability frameworks like ISO 26000 and the UN Sustainable Development Goals (SDGs) (Panagiotakopoulos et al., 2016). - VSM supports sustainable supply chain management, balancing economic and environmental demands (Perko et al., 2024).
Supply Chain Optimization	- VSM minimizes supply chain disruptions by identifying structural weaknesses and implementing systemic solutions. - Enhances stakeholder alignment and systemic flexibility for global supply chains (Espinosa et al., 2023).
Crisis Management	- VSM improves multi-agency responses to crises, such as natural disasters and pandemics (Espinosa et al., 2015). - Provides a robust framework for addressing "wicked problems" requiring inter-organizational coordination (Gallego-García et al., 2019).
Technological Integration	- Emerging technologies such as artificial intelligence, big data analytics, and digital twins are increasingly integrated with VSM to enhance real-time monitoring and decision-making (Lowe et al., 2020; Espinosa et al., 2023). - VSM frameworks demonstrate adaptability for digital transformation and predictive analysis.

Table 3. Summary of key findings across the 23 studies

Authors	Target Country	Research Focus	Research Objectives	Methodology	Key Findings	Future Recommendations
Chan (2011)	Global	SME viability frameworks	Enhance SME systems resilience through VSM analysis.	Case study	VSM supports SME adaptability during crises.	Extend VSM resilience strategies to global SMEs.
Spyridopoulos et al. (2014)	Netherlands	Infrastructure resilience	Use VSM for system adaptability in infrastructure.	Systems analysis	VSM enhances coordination to improve critical systems resilience.	Apply VSM frameworks to healthcare systems.
Espinosa et al. (2015)	Multi-country	Policy adaptability	Use VSM to develop flexible policy systems.	Mixed methods, policy study	VSM improves policy alignment and decision-making adaptability.	Extend VSM policy frameworks for global urban development systems.
Panagiotakopoulos et al. (2016)	UK	Sustainability management using VSM	Analyze VSM's role in achieving sustainability.	Case study	VSM fosters systemic alignment with sustainability objectives.	Refine VSM rules for broader organizational adaptability.
Gallego-García (2019)	Spain	Simulation of VSM	Assess VSM efficiency in systems design.	Simulation-based modeling	VSM improves system efficiency and energy optimization.	Apply VSM models in energy industries for real-world testing.
Vahidi and Aliahmadi (2019)	Global	Hybrid VSM approaches	Combine VSM with other methods for systemic analysis.	Conceptual study	Hybrid approaches improve problem-solving efficiency in complex systems.	Explore VSM hybrid frameworks across multiple industries.
Adham et al. (2020)	Taiwan	Diagnosis of Halal industry systems	Identify inefficiencies in Halal certification.	VSM-based analysis	VSM reveals structural gaps and improves coordination processes.	Extend VSM applications to similar certification systems globally.
Shaw et al. (2020)	Global	Disaster management systems	Propose frameworks for VSM-based disaster response.	Action research	VSM improves systemic disaster risk coordination and mitigation processes.	Apply VSM globally to national disaster risk reduction initiatives.
Cardoso Castro and Espinosa (2020)	European Eco-Community (EEC)	Organizational pathologies, complexity management, and diagnostics	To combine Social Network Analysis (SNA) and the Viable System Model (VSM) for identifying and addressing structural pathologies in organizations.	Action research involving participatory workshops - Data collection via questionnaire, interviews, and field observations	- Integration of VSM and SNA identified weak communication channels, lack of systemic feedback, and poorly aligned operational groups - Provided a robust diagnostic approach for organizational pathologies - The methodology highlighted key actors and structural deficiencies.	- Use advanced computational tools for real-time analysis (e.g., meta-networks and ORA) - Expand the combined framework to other types of organizations - Investigate additional metrics and tools for enhancing diagnostics of structural complexity..

Authors	Target Country	Research Focus	Research Objectives	Methodology	Key Findings	Future Recommendations
Espejo (2021)	UK	Complexity management	Address enterprise complexity with systemic models.	Conceptual study	VSM reduces complexity by improving coordination among organizational layers.	Develop frameworks for enterprise-scale implementation of VSM.
Alves et al. (2021)	Brazil (specifically the state of Tocantins)	Application of the Viable System Model (VSM) to analyze and improve fish farming development policy in Tocantins.	- To diagnose organizational weaknesses in fish farming development policy using VSM. - To enhance socio-economic and environmental sustainability through systemic governance and cybernetic approach.	- Adaptation of VSM for policy analysis. - Use of TASCOI framework to define system identity.	- Identified systemic inefficiencies such as poor coordination and lack of standards for operational units.	- Development of a more integrated framework involving public, private, and academic stakeholders. - Establishment of clear governance structures and technical standards. - Exploration of additional cybernetic models for systematic policy monitoring and management. - Promote stakeholder education and capacity-building initiatives.
Rodriguez-Ulloa (2022)	Peru	Cybernetic governance	Implement VSM to optimize governance frameworks.	Qualitative analysis	VSM improves decision-making processes and reduces inefficiency.	Test VSM in other public governance models in developing nations.
Adham et al. (2022)	Malaysia	Certification system analysis	Identify gaps and strengths in Halal certification.	Case study, VSM diagnosis	VSM improves operational gaps and stakeholder alignment in certifications.	Apply VSM frameworks for other policy-based certifications globally.
Adamides et al. (2023)	Global	Climate change resilience	Apply VSM to improve systemic climate resilience.	Case study	VSM fosters decision-making in critical infrastructure resilience.	Extend frameworks for climate resilience in vulnerable industries.
Perko (2023)	Germany	Circular economy systems	Align VSM with circular economic sustainability.	Case study	VSM supports resilience and sustainability in circular systems.	Expand VSM frameworks for environmental sectors.
Adamides et al. (2023)	Italy	Municipal systems design	Enhance municipal waste systems efficiency using VSM.	Case study, VIPLAN	VSM improves flexibility in managing urban waste systems.	Apply VSM to other urban public service systems globally.
Espinosa et al. (2023)	Multi-country	Organizational resilience	Assess VSM's role in building resilient organizations.	Case study	VSM improves adaptability and long-term resilience in crises.	Scale resilience frameworks using VSM globally.
Steen (2024)	Norway	Investigating the role of interorganizational collaboration in enhancing the viability of	- To identify systemic pathologies and propose improvements to enhance the	- Conducted nine semi-structured interviews with stakeholders. - Document	Identified challenges such as inefficiencies in communication, coordination, and resource allocation.	- Enhance communication and knowledge-sharing mechanisms across agencies. - Develop clearer roles and responsibilities for

Authors	Target Country	Research Focus	Research Objectives	Methodology	Key Findings	Future Recommendations
		disaster response operations, specifically in the context of the Gjerdrum landslide.	overall viability of disaster response systems.	analysis of public reports, media, and evaluation documents.	- Highlighted structural and functional pathologies, including tensions between centralization and decentralization.	interorganizational collaboration.
Sydelko et al. (2024)	Multi-country	Interagency collaboration	Improve multi-stakeholder coordination using VSM.	Mixed-methods, simulation	VSM improves problem-solving across inter-organizational systems.	Develop scalable collaboration tools using VSM principles.
Perko et al. (2024)	Germany	Supply chain management	Develop sustainable supply chains using VSM.	Case study	VSM ensures holistic supply chain sustainability and resilience.	Test VSM in supply chain disruptions caused by crises.

Table 4. Identified research gaps and opportunities

Research Gap	Description	Future Opportunities
Lack of real-world validation	Most studies rely on simulations or conceptual models without real-world testing.	Conduct empirical studies implementing VSM in real-world organizations and industries.
Limited scope of applications	Studies focus on specific sectors (e.g., sustainability, governance).	Explore VSM's scalability across sectors like AI, smart cities, and digital systems.
Reliance on single case studies	Findings are often based on single case studies, limiting generalizability.	Conduct multi-case studies across diverse organizations and geographical regions.
Integration with other methodologies	Few studies explore hybrid approaches combining VSM with systemic tools.	Combine VSM with system dynamics, quantitative modeling, and AI-based methods.
Limited attention to implementation challenges	Practical barriers like resistance and cultural gaps are underexplored.	Identify and address challenges to VSM implementation through empirical studies.
Scalability of VSM frameworks	Focus on SMEs or single organizations, not larger systems.	Develop scalable VSM frameworks for multinational corporations and global networks.
Absence of longitudinal studies	Studies provide cross-sectional analyses without long-term impact assessments.	Conduct longitudinal studies to assess the long-term effectiveness of VSM.
Policy integration challenges	VSM's integration into broader policy ecosystems remains unexplored.	Explore VSM applications in public policy frameworks, especially in developing nations.
Resilience during prolonged crises	Limited focus on prolonged disruptions like pandemics or economic crises.	Evaluate VSM performance in prolonged crises and complex emergency systems.
Data limitations	Lack of quantitative data and metrics in VSM studies.	Incorporate quantitative metrics to improve evaluation and impact measurement.
Circular economy integration	Few studies apply VSM in circular economy initiatives.	Design VSM models for circular economies, waste management, and industrial ecology.
Interdisciplinary research	Limited exploration in interdisciplinary fields like AI and digital systems.	Combine VSM with emerging technologies to address complex and dynamic systems.
Stakeholder engagement processes	Limited focus on stakeholder engagement in VSM implementation.	Develop frameworks to improve stakeholder buy-in and systemic adoption of VSM.

The bibliometric summary (Figure 4) highlights a moderate annual growth rate (1.45%), indicating a steady but not exponential expansion of the research domain. With 768 documents published across 378 sources, the field demonstrates a diverse publication landscape, supported by 1,110 authors, yet a relatively low international co-authorship rate (16.8%), suggesting limited global collaboration. The average number of citations per document (9.151) reflects a reasonably strong impact, although the document's average age (12.2 years) suggests reliance on older foundational works. The high number of unique keywords (1,778) indicates a broad thematic scope, making this research area interdisciplinary and evolving.

The bibliometric visualization of Annual Scientific Production in Figure 5 reveals an initial slow growth phase (1977–1999), followed by a rapid expansion (2000–2010), indicating an increasing scholarly interest and theoretical advancements. The period from 2010 to 2022 reflects peak productivity, albeit with fluctuations, likely driven by funding cycles, policy changes, and emerging interdisciplinary integrations. The sharp decline after 2023 is likely due to incomplete data for recent years, rather than an actual drop in research output. This pattern aligns with Price's Law of Scientific Growth, suggesting a field that has matured but may now be transitioning into new research directions.



Figure 4. The bibliometric summary

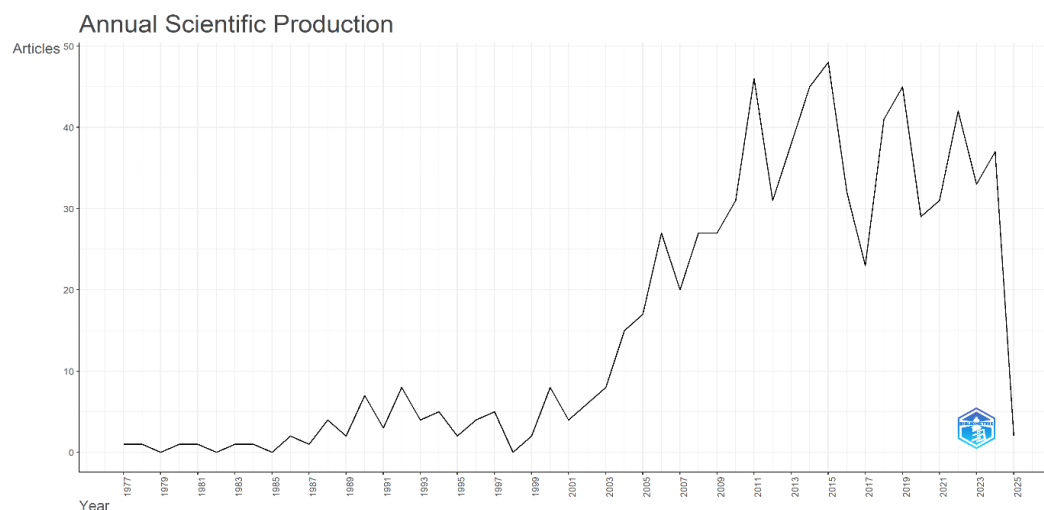


Figure 5. The bibliometric visualization of annual scientific production

The bibliometric visualization of document types in [Figure 6](#) reveals that journal articles (55.6%) dominate scholarly contributions, indicating a strong emphasis on peer-reviewed research. Conference papers (31%) represent a significant portion, reflecting the dynamic and evolving nature of the field through the rapid dissemination of knowledge. Book chapters (6.1%) and reviews (3.2%) suggest ongoing theoretical advancements and conceptual synthesis. The presence of editorials, errata, and short surveys ($\leq 0.1\%$) is minimal, indicating limited engagement in opinion-based or corrigendum literature. This distribution aligns with scientific communication trends, where journal articles serve as the primary medium for rigorous academic discourse, while conferences act as platforms for emerging innovations.

Documents by type

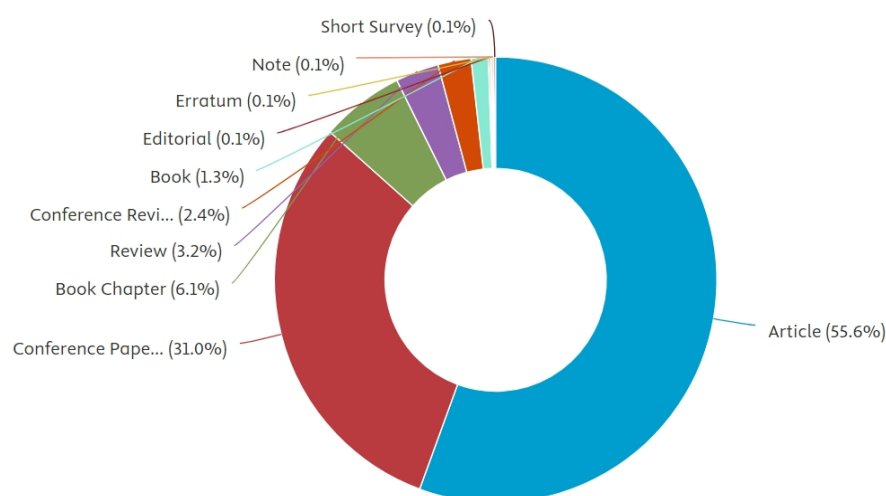


Figure 6. The bibliometric visualization of document types

The bibliometric analysis of documents by subject area in [Figure 7](#) reveals a strong interdisciplinary nature, with Computer Science (21.9%), Engineering (18.6%), and Business, Management (16.1%) being the dominant fields, indicating a technological and managerial research focus. Social Sciences (12.9%) and Decision Sciences (9.4%) suggest significant engagement with policy-making and strategic decision-making frameworks. The presence of Mathematics (9.1%) implies a quantitative or computational approach to problem-solving. The lower representation of Economics (2.6%), Arts and Humanities (1.5%), and Medicine (1.5%) suggests that while peripheral, these disciplines contribute theoretical, ethical, or applied insights. This distribution aligns with modern research trends where digital transformation, engineering solutions, and managerial decision-making are interlinked.

The bibliometric analysis, using Bradford's Law, identifies the core journals that contribute the most significant volume of research in the field, highlighting their central role in disseminating knowledge. The shaded area represents the most influential sources, including journals like *Kybernetes*, *Systemic Practice and Action Research*, and *Systems Research and Behavioral Science*, which are foundational to this domain. The steep decline beyond the core zone indicates a long-tail distribution, suggesting that while many peripheral sources exist, their contribution is minimal compared to the core sources. It aligns with Bradford's Law, which states that a small set of journals accounts for the majority of relevant literature. Identifying these core sources is crucial for researchers aiming to publish in high-impact venues and track emerging scholarly debates ([Figure 8](#)).

Documents by subject area

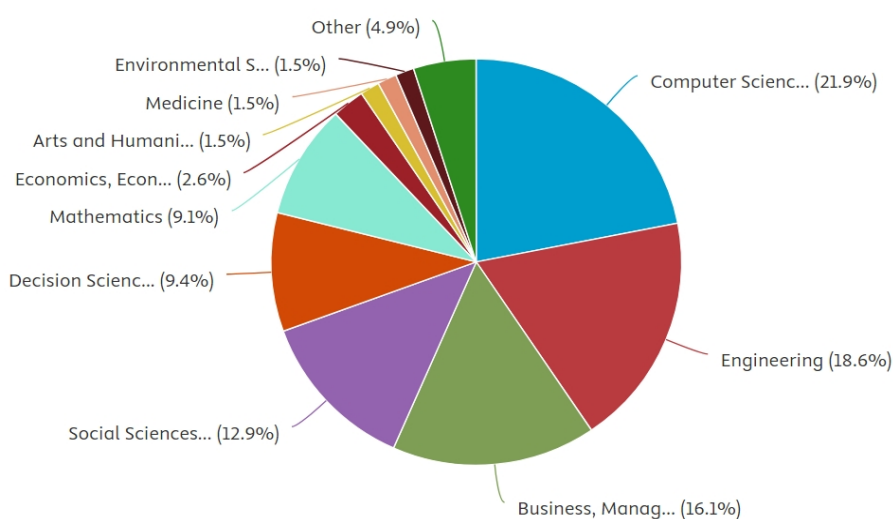


Figure 7. The bibliometric visualization of document types

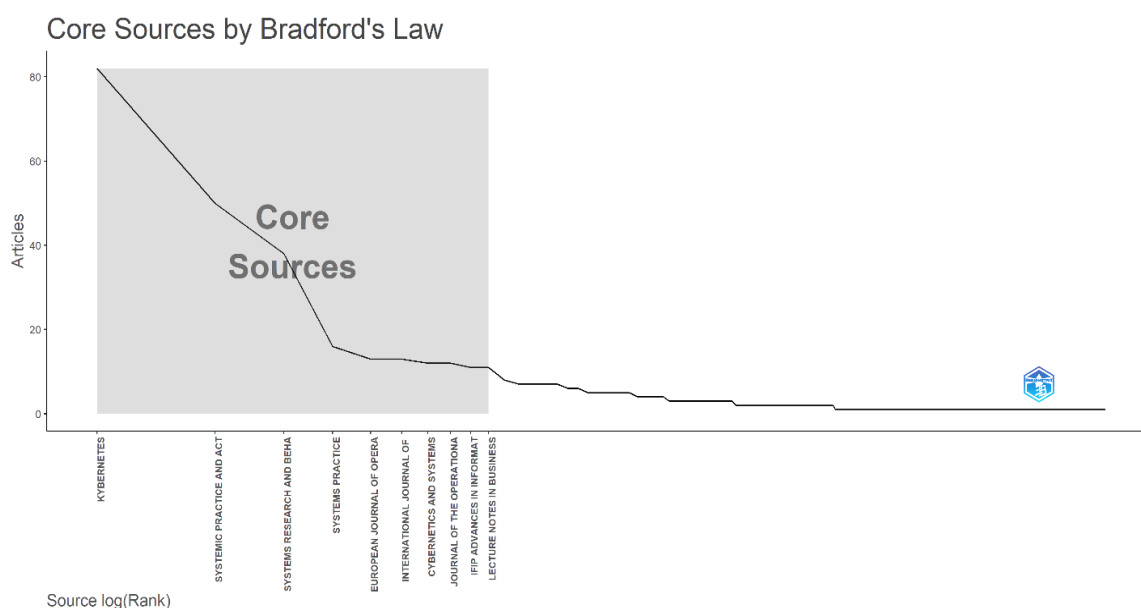


Figure 8. The bibliometric analysis using bradford's law

The word cloud visualization (Figure 9) highlights "Viable System Model" and "Cybernetics" as the dominant research themes, indicating a strong conceptual foundation in systems thinking and organizational viability. Keywords such as "decision-making," "information systems," and "sustainable development" suggest interdisciplinary applications, particularly in management, governance, and technology-driven solutions. The presence of "design/methodology/approach" implies a focus on theoretical and practical frameworks, supporting methodological advancements. Including "Stafford Beer" and "systems modeling" reinforces the field's theoretical lineage and continued evolution. This keyword analysis reflects a dynamic research landscape that integrates systems science, decision theory, and digital transformation.



Figure 9. The word cloud visualization

The trend topic analysis (Figure 10) highlights the evolution of research themes over time, with cybernetics, system theory, and viable system models (VSM) emerging as foundational concepts. The growing interest in big data, complex networks, decision-making, and sustainable development has led to a shift toward technological and governance-oriented applications in recent years. The increasing frequency of terms like energy management, behavioral research, and innovation suggests an interdisciplinary expansion of VSM into environmental and organizational domains. The presence of wicked problems and problem structuring reflects a contemporary focus on complex, systemic challenges. This trajectory aligns with the digital transformation of systems science, bridging theoretical advancements with real-world problem-solving.

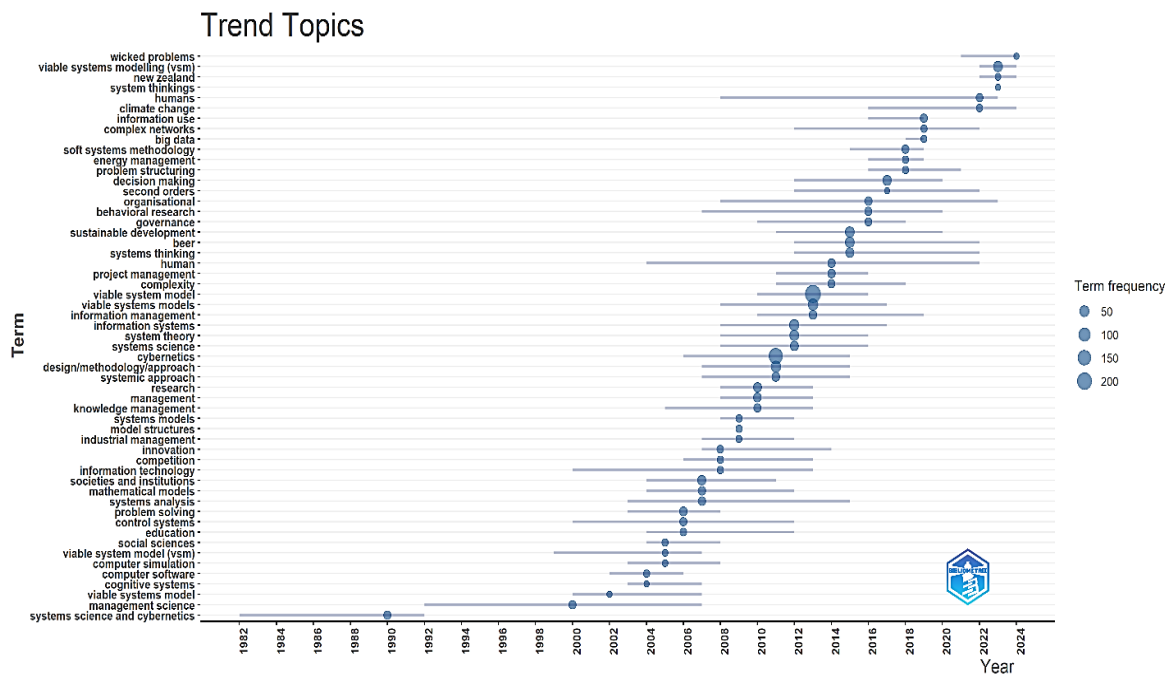


Figure 10. The trend topic analysis

The co-word network clustering analysis in Figure 11 illustrates the conceptual landscape of VSM research, with "cybernetics" and "methodology/approach" as dominant themes, reflecting strong theoretical underpinnings. The red cluster focuses on decision-making, complexity, and systems dynamics, indicating applications in organizational strategy and problem structuring. The blue cluster links VSM to management science, governance, and knowledge management, emphasizing its role in institutional decision-making. The green cluster, containing climate change and complex networks, suggests emerging interdisciplinary applications in sustainability and digital ecosystems. The purple cluster, encompassing operations research and mathematical modeling, highlights quantitative and computational methodologies that support

VSM. The network structure confirms VSM's expanding interdisciplinary relevance, integrating systems thinking, decision theory, and computational modeling. This analysis underscores VSM's adaptability, positioning it at the intersection of organizational resilience, systemic governance, and digital transformation.

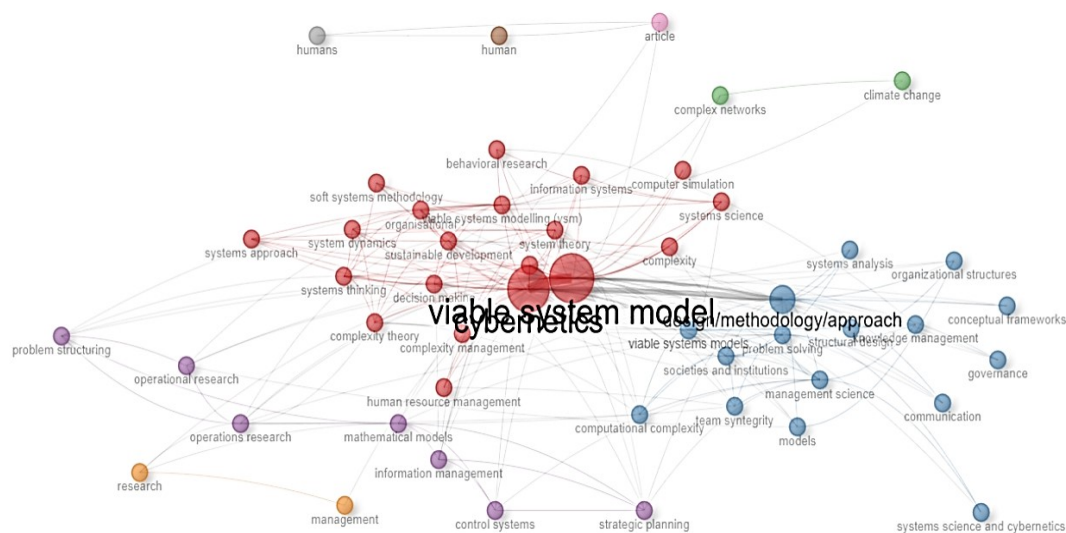


Figure 11. The co-word network clustering analysis

The thematic map analysis in [Figure 12](#) categorizes research themes based on development (density) and relevance (centrality), providing insights into the VSM research landscape. The motor themes (upper-right quadrant), including VSM, cybernetics, and organizational process, indicate well-developed and highly relevant topics driving the field. The basic themes (lower-right quadrant), such as systems science, system theory, and system dynamics, form the conceptual foundation of the domain. The niche themes (upper-left quadrant), including wicked problems, crime, and government agencies, suggest specialized but less influential areas. The emerging or declining themes (lower-left quadrant), such as sustainability, organizational framework, and virtual reality, indicate potential future directions or declining interest. The map highlights VSM's strong interdisciplinary integration, connecting governance, healthcare, and digital transformation. Complex networks and adaptive systems signal growing applications in computational and artificial intelligence-driven systems thinking. Future research may benefit from expanding interdisciplinary collaborations to integrate decision sciences, sustainability, and digital governance frameworks.

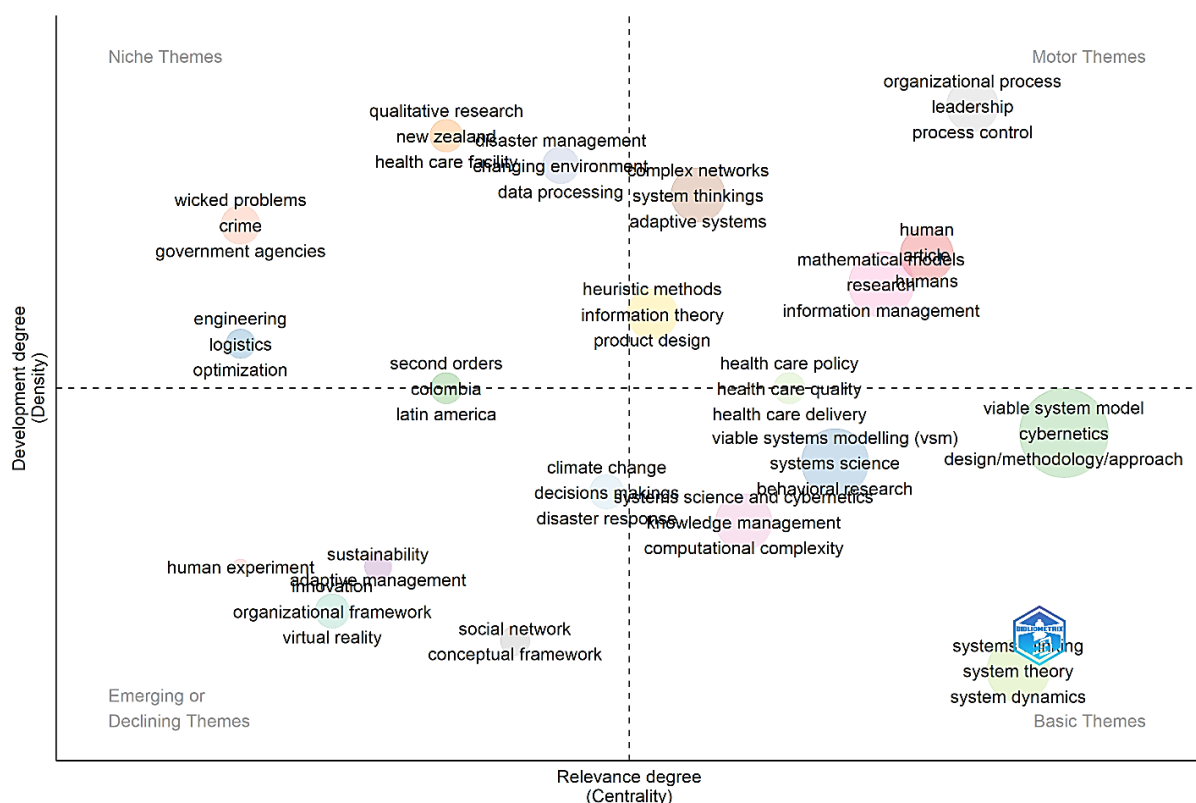


Figure 12. The thematic map analysis

4. Discussion and conclusion

This systematic review evaluates the breadth and depth of the VSM applications across various domains, synthesizing findings from 21 studies. By critically analyzing the role of VSM in managing complexity, the study highlights its contributions to improving systemic resilience, enhancing decision-making, and facilitating organizational adaptability across various domains, including governance, healthcare, sustainability, supply chains, and crisis management. Subsequently, based on the findings from the research, we will examine and address the research questions.

RQ1: In what domains has the Viable System Model been applied?

The systematic review identifies six major domains where VSM has been widely applied: governance, healthcare, sustainability, supply chain optimization, crisis management, and technological integration. In governance, VSM has improved public administration decision-making, coordination, and policy alignment. It has strengthened resilience, resource allocation, and systemic coordination in healthcare, particularly during crises like the COVID-19 pandemic. Sustainability applications include their role in aligning organizational processes with environmental and social sustainability goals, particularly in circular economy models and sustainable supply chain management. VSM enhances stakeholder integration, system

flexibility, and risk management in supply chains. In crisis management, VSM has proven effective in multi-agency collaboration, systemic coordination, and disaster resilience. Technological integration highlights VSM's adaptability in AI-driven decision-making, big data analytics, and digital transformation initiatives.

VSM, as highlighted in the document, has been applied in a wide range of interdisciplinary fields, such as VSM in management and governance (in organizational strategy, decision-making, and governance, particularly in knowledge management and institutional decision-making), cybernetics and systems science (for system modeling and complexity management), information systems and digital transformation (in digital ecosystems, information systems, and emerging technologies like artificial intelligence and big data), sustainability and environmental sciences (for analyzing climate change, energy management, and sustainable development), operations research and computational methods (mathematical modeling, complex networks, and quantitative approaches to problem structuring), and public policy and government organizations (in governance structures, policy-making, and addressing social challenges such as crime prevention and organizational resilience).

RQ2: What insights have emerged from these applications?

A key finding is that VSM enhances systemic resilience, adaptability, and decentralized decision-making across different industries. The review highlights its effectiveness in identifying systemic inefficiencies, reducing complexity, and improving multi-layered governance structures. Integrating emerging technologies, such as digital twins and AI, demonstrates the model's ability to evolve with modern challenges. In sustainability, the alignment of VSM with UN Sustainable Development Goals (SDGs) suggests its growing relevance in addressing environmental and organizational difficulties. However, despite its conceptual strengths, the study reveals a gap in empirical validation, as many studies rely on theoretical and simulation-based models rather than real-world implementation.

Several key insights have emerged from applying VSM across domains: Interdisciplinary Nature, Adaptability and Resilience, Decision-Making and Complexity Management, Digital Transformation and Innovation, Sustainability Applications, and Integration with Systemic Governance.

RQ3: What challenges and opportunities exist for the VSM in addressing contemporary systemic issues?

The study identifies several key challenges in VSM implementation. One of the primary concerns is scalability, particularly in small and medium enterprises (SMEs) and large

multinational organizations. Another challenge is the lack of empirical studies, as most research remains conceptual or simulation-based, limiting real-world validation. Resistance to change and low systems literacy in organizations also hinder the widespread adoption of VSM. However, there are significant opportunities for further research, particularly in interdisciplinary fields such as AI, smart cities, and digital governance. The study suggests the development of hybrid frameworks that integrate VSM with quantitative modeling, AI, and predictive analytics. Future research should also focus on longitudinal studies to assess the long-term impact of VSM applications in various industries.

Our analysis identifies key challenges associated with the Viable System Model (VSM), including the complexity of implementation, the lack of extensive empirical validation, limitations in international collaborations, and the need to adapt to emerging technologies. At the same time, there are potential opportunities for developing and applying this model, particularly in digital applications, to enhance sustainability and resilience, strengthen the connection between governance and decision science, and leverage significant computational modeling.

4.1. Theoretical contributions and key insights

The findings reaffirm VSM's foundational relevance as a systemic approach for organizational management, while extending its utility to address contemporary challenges. These insights contribute to both the theoretical evolution of VSM and its practical adaptability.

4.1.1. Governance systems: Enhancing coherence and adaptability

Governance remains the most prominent domain of VSM application. Studies such as [Espinosa et al. \(2015\)](#) and [Pollock and Steen \(2021\)](#) illustrate VSM's capacity to address systemic inefficiencies, fragmentation, and communication barriers in public administration. By promoting decentralized decision-making, VSM provides a mechanism for striking a balance between central oversight and local autonomy. This approach enhances policy coherence and institutional adaptability in multi-level governance systems, offering a robust solution to governance challenges in both developing and developed economies. The systemic properties of VSM align with emerging needs in governance, particularly in complex, inter-agency collaborations. [Gallego-García et al. \(2019\)](#) demonstrate how VSM can foster trust, transparency, and systemic coordination in addressing wicked problems, such as regional development and disaster response. It highlights VSM's role as a tool for facilitating adaptive governance frameworks that can address multifaceted societal challenges.

4.1.2. Sustainability: Aligning organizational goals with environmental objectives

The review highlights VSM's increasing relevance to sustainability, where it enables organizations to align operational processes with long-term environmental goals. [Espinosa et al. \(2023\)](#) and [Perko \(2024\)](#) demonstrate how VSM frameworks incorporate circular economy principles, enabling systemic solutions to sustainability challenges. These studies highlight VSM's potential to support the United Nations' Sustainable Development Goals (SDGs) by fostering adaptive systems that can balance ecological, economic, and social demands. The application of VSM in sustainable supply chains further underscores its value. By identifying structural inefficiencies and fostering stakeholder integration, VSM enables organizations to build resilience against disruptions and maintain operational alignment with sustainability targets. It extends VSM's utility to globalized supply chain networks, particularly in industries characterized by resource constraints and environmental pressures.

4.1.3. Healthcare systems: Building resilience and operational efficiency

Although underexplored compared to governance and sustainability, healthcare emerges as a key domain for VSM applications. Studies such as [Espinosa et al. \(2023\)](#) and [Pollock and Steen \(2021\)](#) demonstrate how VSM enhances healthcare resilience during crises, including pandemics and resource shortages. By improving systemic coordination, resource allocation, and communication, VSM provides a robust framework for managing complex healthcare networks. The review reveals VSM's ability to optimize patient care pathways, reduce systemic waste, and enhance operational stability under pressure. These findings highlight VSM as a valuable tool for addressing healthcare challenges in both developed and resource-constrained settings, particularly as healthcare systems face growing demands and complexity.

4.1.4. Supply chain systems: Managing complexity in dynamic environments

The results demonstrate VSM's applicability to modern supply chains, where it minimizes disruptions, improves systemic flexibility, and enhances stakeholder alignment. [Perko et al. \(2024\)](#) and [Pollock and Steen \(2021\)](#) illustrate how VSM enables organizations to respond to supply chain variability through feedback mechanisms and systemic redesigns. This positions VSM as a critical tool for improving supply chain resilience, particularly in light of global uncertainties such as pandemics, geopolitical risks, and technological disruptions.

4.1.5. *Crisis management: Multi-Agency collaboration and systemic resilience*

Crisis management emerges as a key area of VSM application, where its systemic principles enable multi-agency collaboration, adaptive decision-making, and the building of resilience. Studies, such as those by Gallego-García et al. (2019), highlight VSM's ability to enhance systemic coordination during natural disasters, governance crises, and other disruptions. By fostering real-time information flows and dynamic feedback loops, VSM improves organizational responses to unpredictable challenges, making it an indispensable tool for managing systemic risks.

Our review of the studies conducted found that the diversity in the VSM areas is highly flexible and provides systemic solutions to existing challenges in governance, healthcare, sustainability, supply chains, and crisis management. Its principles align with the growing need for resilient and adaptable systems that respond to contemporary organizational challenges. Our findings emphasize the applicability of VSM in enhancing decentralized decision-making, improving systemic resilience, and enabling multi-agency collaboration. Integrating VSM with emerging technologies further strengthens its applicability in technology-driven and data-centric environments. Another finding is that theoretical advancements can extend the exploration of the theoretical boundaries of VSM and demonstrate its relevance to emerging fields such as sustainability and crisis management. This review highlights the role of VSM as a systemic tool for aligning organizational structures with the dynamic needs of the environment.

While the findings of this study provide valuable insights into the distribution and applications of VSM, several limitations must be acknowledged. Firstly, the study relied exclusively on the Scopus database for data extraction. It may have omitted relevant studies indexed in other databases, such as Web of Science, IEEE Xplore, or discipline-specific repositories. As a result, the findings may not fully reflect the global landscape of VSM applications, potentially introducing selection bias. Another significant limitation is that the study covers multiple domains (governance, healthcare, sustainability, supply chains, and crisis management), but it does not profoundly explore sector-specific challenges. The applicability of VSM in education, agriculture, and digital governance remains underexplored, limiting insights into its full interdisciplinary potential. A significant limitation is the lack of empirical validation for many reviewed applications.

Several studies are conceptual or simulation-based, making it difficult to assess the real-world impact of VSM in dynamic environments. Future research should conduct longitudinal and

multi-case studies to validate the model's effectiveness. Despite its theoretical robustness, the practical implementation of VSM poses challenges, including organizational resistance, low systems literacy, and adaptation difficulties in complex structures. These factors may hinder adoption in real-world settings, requiring simplified models or hybrid approaches. Most studies lack quantitative validation, relying instead on qualitative assessments that may be subject to bias. There is an absence of standardized metrics to measure the impact of VSM interventions, making it challenging to compare effectiveness across different contexts. Future research should expand data sources, conduct multi-case and longitudinal studies, explore interdisciplinary applications, and develop scalable VSM models for SMEs to address these limitations. Integrating quantitative metrics and hybrid approaches will enhance the practical relevance and adoption of these methods. Lastly, the study does not assess the long-term impacts or sustainability of VSM applications. Future research could focus on measuring the tangible and intangible outcomes of VSM over extended periods, such as cost savings, process improvements, and organizational cultural transformations. By addressing these limitations, future research can build on the insights presented here to provide a more comprehensive and nuanced understanding of VSM's potential across diverse contexts.

Disclosure statement

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

References

- Adamides, E.D., Georgousoglou, K. and Mouzakis, Y., 2023. Designing a Flexible and Adaptive Municipal Waste Management Organisation Using the Viable System Model. *Sustainability*, 15(18), p.13323. <https://doi.org/10.3390/su151813323>.
- Adamides, E.D., Katopodis, T., Mountouris, A. and Sfetsos, A., 2023. Organising for Resilience to Climate Change in Critical Infrastructures: The Application of Viable System Model in an Oil Refinery. *Systemic Practice And Action Research*, 36(4), pp.609-640. <https://doi.org/10.1007/s11213-022-09623-x>.
- Adham, K.A., Muhamad, N.S.A. and Said, M.F., 2020. Diagnosing the Halal Industry of Taiwan: A viable system model approach. *Jurnal Pengurusan*, 58, pp.169-179. <http://dx.doi.org/10.17576/pengurusan-2020-58-14>.
- Adham, K.A., Rahim, A.A., Masood, A. and Said, M.F., 2022. Evolution of the Malaysian Halal Certification System: Viable System Model as the Diagnostic Framework. *Jurnal Pengurusan*, 66. <https://doi.org/10.17576/pengurusan-2022-66-03>.
- Alves, J.M., Rodrigues, W., Vergara, F.E., Souza, F.N. and Terra, L.A.A., 2021. From the black box to the fish farming development policy project: A diagnosis from the viable system model. *Systems Research and Behavioral Science*, 38(4), pp.459-472. <http://dx.doi.org/10.1002/sres.2675>.

- Ashby W. R. 1956. *An Introduction to Cybernetics*. London: Chapman & Hall.
- Beer S. 1972. *Brain of the Firm*. London: Allen Lane.
- Beer S. 1979. *The Heart of Enterprise*. Chichester: John Wiley & Sons.
- Beer S. 1985. *Diagnosing the System for Organizations*. Chichester: John Wiley & Sons.
- Cardoso Castro, P.P. and Espinosa, A., 2020. Identification of organisational pathologies: Exploration of social network analysis to support the viable system model diagnostic. *Kybernetes*, 49(2), pp.285-312. <http://dx.doi.org/10.1108/K-10-2018-0557>.
- Chan, J.W., 2011. Enhancing organisational resilience: application of viable system model and MCDA in a small Hong Kong company. *International Journal of Production Research*, 49(18), pp.5545-5563. <http://dx.doi.org/10.1080/00207543.2011.563829>.
- Checkland P. 1981. *Systems Thinking, Systems Practice*. Chichester: John Wiley & Sons.
- Espejo R, & Harnden R. (Eds.). 1989. *The Viable System Model: Interpretations and Applications of Stafford Beer's VSM*. Chichester: Wiley.
- Espejo, R., 2021. The enterprise complexity model: An extension of the viable system model for emerging organizational forms. *Systems Research and Behavioral Science*, 38(6), pp.721-737. <http://dx.doi.org/10.1002/sres.2735>.
- Espinosa A, and Walker J. 2011. *A Complexity Approach to Sustainability: Theory and Application*. London: Imperial College Press.
- Espinosa, A., Harnden, R. and Walker, J., 2007. Beyond hierarchy: a complexity management perspective. *Kybernetes*, 36(3/4), pp.333-347. <https://doi.org/10.1108/03684920710746919>.
- Espinosa, A., Reficco, E., Martínez, A. and Guzmán, D., 2015. A methodology for supporting strategy implementation based on the VSM: A case study in a Latin-American multi-national. *European Journal of Operational Research*, 240(1), pp.202-212. <https://doi.org/10.1016/j.ejor.2014.06.014>.
- Espinosa, A.M., Walker, J., Grover, K. and Vachkova, M.V., 2023. The viability and sustainability approach to support organisational resilience: Learning in a recent case study in the health sector. *Systems Research and Behavioral Science*, 40(4), pp.689-700. <http://dx.doi.org/10.1002/sres.2951>.
- Flood R. L, & Jackson M. C. 1991. *Creative Problem Solving: Total Systems Intervention*. Chichester: John Wiley & Sons.
- Gallego-García, S., Reschke, J. and García-García, M., 2019. Design and simulation of a capacity management model using a digital twin approach based on the viable system model: Case study of an automotive plant. *Applied Sciences*, 9(24), p.5567. <http://dx.doi.org/10.3390/app9245567>.
- Hildreth A. J, & Kimble C. 2004. Knowledge networks: Innovation through communities of practice. *Knowledge Management Research & Practice*, 2(1), pp.53-67. <https://doi.org/10.1057/palgrave.kmrp.8500026>.
- Hoverstadt P. 2008. *The Fractal Organization: Creating Sustainable Organizations with the Viable System Model*. Chichester: John Wiley & Sons.
- Jackson M. C. 2003. *Systems Thinking: Creative Holism for Managers*. Chichester: John Wiley & Sons.
- Leonard, A., 2009. The viable system model and its application to complex organizations. *Systemic*

- practice and action research*, 22(4), pp.223-233. <https://doi.org/10.1007/s11213-008-9108-z>.
- Lowe, D., Espinosa, A. and Yearworth, M., 2020. Constitutive rules for guiding the use of the viable system model: Reflections on practice. *European Journal of Operational Research*, 287(3), pp.1014-1035. <https://doi.org/10.1016/j.ejor.2020.05.030>.
- Moher D, Liberati A, Tetzlaff J, Altman D. G, and PRISMA Group*, T. 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Annals of internal medicine*, 151(4), pp. 264-269. <https://doi.org/10.1371/journal.pmed.1000097>.
- Panagiotakopoulos, P.D., Espinosa, A. and Walker, J., 2016. Sustainability management: insights from the viable system model. *Journal of Cleaner Production*, 113, pp.792-806. <https://doi.org/10.1016/j.jclepro.2015.11.035>.
- Perko, I., del Gaudio, G. and Potocan, V., 2024. Sustainable supply chains–Designing a requisite holistic model. *Business Ethics, the Environment & Responsibility*. <https://doi.org/10.1111/beer.12707>.
- Perko, I., 2023. Data sharing concepts: a viable system model diagnosis. *Kybernetes*, 52(9), pp.2976-2991. <https://doi.org/10.1108/K-04-2022-0575>.
- Pollock, K. and Steen, R., 2021. Total defence resilience: Viable or not during COVID-19? A comparative study of Norway and the UK. *Risk, Hazards & Crisis in Public Policy*, 12(1), pp.73-109. <https://doi.org/10.1002/rhc3.12207>.
- Rodriguez-Ulloa, R., 2022. Cybernetic governance of the Peruvian State: a proposal. *AI & society*, 37(3), pp.1207-1229. <https://doi.org/10.1007/s00146-021-01329-3>.
- Schwaninger, M., 2006. Design for viable organizations: The diagnostic power of the viable system model. *Kybernetes*, 35(7/8), pp.955-966. <https://doi.org/10.1108/03684920610675164>.
- Shaw, D., Fattoum, A., Moreno, J. and Bealt, J., 2020. A structured methodology to peer review disaster risk reduction activities: The Viable System Review. *International journal of disaster risk reduction*, 46, p.101486. <https://doi.org/10.1016/j.ijdrr.2020.101486>.
- Spyridopoulos, T., Topa, I.A., Tryfonas, T. and Karyda, M., 2014, June. A holistic approach for cyber assurance of critical infrastructure with the viable system model. In *IFIP International Information Security Conference* (pp. 438-445). Berlin, Heidelberg: Springer Berlin Heidelberg. <http://dx.doi.org/10.13140/2.1.2012.3847>.
- Steen, R., Roud, E., Torp, T.M. and Hansen, T.A., 2024. The impact of interorganizational collaboration on the viability of disaster response operations: The Gjerdrum landslide in Norway. *Safety science*, 173, p.106459. <http://dx.doi.org/10.1016/j.ssci.2024.106459>.
- Sydelko, P., Espinosa, A. and Midgley, G., 2024. Designing interagency responses to wicked problems: A viable system model board game. *European Journal of Operational Research*, 312(2), pp.746-764. <http://dx.doi.org/10.1016/j.ejor.2023.06.040>.
- Tugwell, P. and Tovey, D., 2021. PRISMA 2020. *Journal of Clinical Epidemiology*, 134, pp.A5-A6. <https://doi.org/10.1016/j.jclinepi.2021.04.008>.
- Vahidi, A. and Aliahmadi, A., 2019. Describing the necessity of multi-methodological approach for viable system model: case study of viable system model and system dynamics multi-methodology. *Systemic Practice and Action Research*, 32(1), pp.13-37. <https://link.springer.com/article/10.1007/s11213-018-9452-0>.



Enhancing Sustainable Social Banking Performance through Artificial Intelligence: A System Dynamics Analysis of Iranian Cooperative Banks

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ABSTRACT

With the expansion of innovative technologies, the banking industry has faced profound transformations. Artificial intelligence, as one of the most significant of these technologies, has the potential to transform the nature of banking services; however, its impact on social banking, particularly in cooperative banks, has received less attention. This research aims to investigate the impact of artificial intelligence functions on the performance of social banking in Iranian cooperative banks, utilizing a system dynamics approach. The study adopts a mixed approach (qualitative-quantitative). In the qualitative section, key variables were identified using an expert panel, and in the quantitative section, a system dynamics model was developed using Vensim software. The stock-flow model simulated the relationships between main variables, including sustainable development, bank reputation, unpredictable liquidity, non-performing loans, and artificial intelligence infrastructure, over 10 years (2021-2031). The results of the sensitivity analysis and scenario development demonstrated that strategic investments in artificial intelligence infrastructure, enhanced data protection protocols, and improved financial transparency contribute significantly to an enhanced bank reputation, substantially reduce unpredictable liquidity fluctuations, and notably decrease non-performing loans, thereby supporting sustainable banking operations. Model validation tests, including boundary conditions tests, structural tests, uncertainty tests, and integration tests, confirmed the accuracy of the relationships. This model can serve as a tool for decision-making and policy-making regarding the application of artificial intelligence in the country's social banking system.

Keywords

Social banking, Artificial intelligence, System Dynamics, Liquidity, Cooperative banks.

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1. Introduction

The banking industry has undergone remarkable transformations in recent decades. Technological advancements, particularly in the field of artificial intelligence (AI), have paved the way for new forms of banking services that respond to the diverse needs of customers and society (Jakšič and Marinč, 2019). In this context, social banking has emerged as a novel approach within the banking system, aiming to combine financial goals with social and environmental responsibilities (Ozili, 2025). Social banking seeks not only profitability but also to create sustainable value for society, the environment, and the economy (de Andreis et al., 2024).

The integration of AI technologies with social banking principles represents a transformative opportunity to enhance sustainability across all three dimensions—economic, social, and environmental. By leveraging AI's analytical capabilities, cooperative banks can achieve more efficient resource allocation, improved risk management, and enhanced customer service delivery while maintaining their commitment to social responsibility and community development (Gyau et al., 2024). This research specifically examines how AI can facilitate sustainable banking practices that strike a balance between profitability and social impact, thereby contributing to the broader goal of achieving sustainable financial systems.

In recent years, with the introduction of AI into financial services, a major transformation has occurred in the way banking services are delivered. Intelligent systems can analyze vast amounts of data, identify hidden patterns, and make more accurate credit decisions (Sadok et al., 2022). It is particularly impactful in cooperative banks, whose primary purpose is to serve their members and the local community (Venantzi and Matteucci, 2022).

Cooperative banks in many countries face multiple challenges, including resource limitations, unpredictable liquidity, and high levels of non-performing loans (Degregori et al., 2025). On the other hand, these banks, due to their social nature, have high potential for developing social banking (Korzeb et al., 2024). The use of AI can be an effective solution to overcome existing challenges and improve the performance of these banks (Rahman et al., 2021).

Studies show that implementing AI-based systems can lead to increased accuracy in credit risk assessment, improved liquidity management, and enhanced customer trust (Al-Sartawi, 2022). For example, machine-learning (ML) algorithms can analyse customer behaviour, predict loan payment patterns, and reduce default risk (Karki et al., 2025). Additionally, AI

systems can analyse big data to predict liquidity fluctuations and help better manage financial resources (Iannaci and Gideon, 2020).

Despite the high potential of AI in transforming the banking industry, few studies have been conducted on the impact of this technology on social banking, particularly cooperative banks. Most existing research has focused on technical aspects of AI or commercial banks (Su and Wang, 2025). Furthermore, the lack of dynamic models to understand the complex interactions between variables affecting AI functions in social banking represents an important gap in the existing literature (Stavropoulou et al., 2023).

This research gap reflects a fundamental system-level problem: while AI technologies offer significant potential for transforming banking operations, the complex interdependencies and feedback mechanisms that determine successful AI implementation in social banking contexts remain poorly understood. The challenge is not merely technical implementation, but understanding how AI adoption creates cascading effects across multiple dimensions of bank performance—from operational efficiency and risk management to customer satisfaction and community impact—within the unique organizational and social context of cooperative banks.

In this context, the present research aims to study the impact of AI functions on social banking performance using a system dynamics approach in Iranian cooperative banks. The system dynamics method is a powerful tool for analyzing complex systems and understanding non-linear relationships between variables. This approach addresses the core research problem by examining how AI technologies create reinforcing feedback loops between infrastructure investment, service quality improvement, customer satisfaction, and resource mobilization in cooperative banks. The system-level analysis recognizes that sustainable AI-enabled transformation requires understanding not just individual technology impacts, but the dynamic interactions that either enable virtuous cycles of improvement or create implementation barriers that limit transformation potential. Using this method, we can examine the impact of changes in key variables such as AI infrastructure, unpredictable liquidity, and non-performing loans on the overall performance of the social banking system over time.

The importance of this research stems from the fact that decision-making regarding investment in AI technologies requires a deep understanding of the long-term impacts of this investment on bank performance. The dynamic model presented in this research enables the simulation of various scenarios, helping cooperative bank managers make more informed decisions about the application of AI.

The dynamic hypothesis guiding this research posits that AI implementation in social banking creates interconnected, reinforcing loops where enhanced technological capabilities improve risk assessment and service personalization, leading to increased customer satisfaction and bank reputation, which in turn enables better resource mobilization for further AI investments. However, this process is constrained by resource allocation limitations and implementation challenges that can create balancing effects, making the timing and sequencing of AI investments critical for achieving sustainable transformation.

Furthermore, the results of this research can significantly contribute to the development of social banking in Iran. Social banking, with its focus on supporting small and medium-sized businesses, empowering vulnerable groups, and promoting sustainable development, plays a crucial role in achieving the country's economic and social objectives. Combining this approach with AI capabilities can lead to innovative sustainable banking models that simultaneously improve economic efficiency, enhance social impact, and contribute to environmental sustainability through optimized operations and resource management.

Following this introduction, and after reviewing the literature and presenting the dynamic hypothesis, the research methodology is discussed. Then, the findings from modelling and simulation are introduced, and finally, conclusions and practical recommendations are provided.

2. Literature review

2.1. Social banking and sustainable development

Social banking, as defined by Pérez (2017), integrates financial objectives with social and environmental considerations. Research demonstrates that social banking plays a crucial role in directing capital toward sustainable economic activities (Andrikopoulos, 2020) and supporting the sustainability of small and medium-sized businesses through tailored financial services and collaborative networks (Stavropoulou et al., 2023).

2.2. Cooperative banks and their challenges

Cooperative banks, which focus on serving members and local communities, represent a sustainable banking model with greater stability than commercial banks during crisis conditions (Venantzi and Matteucci, 2022). However, they face challenges including credit risk management (Kil et al., 2021) and limited adoption of modern technologies and digital marketing strategies (Nethala et al., 2022).

2.3. AI in the banking industry

AI serves as a primary driver of digital transformation in banking, enabling improved decision-making through the analysis of big data (Zamany et al., 2024). AI applications include service quality prediction (Castelli et al., 2016), strengthening bank-customer relationships through personalized services (Jakšič and Marinč, 2019), and facilitating technology adoption based on perceived usefulness and trust factors (Rahman et al., 2021).

2.4. AI-Based credit analysis

AI significantly enhances credit analysis and risk management capabilities. Research shows that AI algorithms enhance credit decision accuracy and reduce default rates (Sadok et al., 2022), facilitate effective credit scoring in microfinance (Terko et al., 2019), and support the evaluation of efficiency in cooperative banks through hybrid analytical methods (Gautam et al., 2024).

2.5. AI and liquidity management

AI technologies address liquidity management challenges through predictive capabilities. Studies demonstrate that intelligent systems optimize liquidity management by predicting cash flows (Fourie and Bennett, 2019) and enhance decision-making in capital management through market data analysis and financial trend prediction (Radhakrishna et al., 2024).

2.6. Social banking and AI: Towards a sustainable model

Limited research has explored the specific impact of AI on social banking. Recent studies have explored the relationship between social business, AI, and sustainability (de Andreis et al., 2024), AI's role in sustainable finance through improved transparency and risk reduction (Al-Sartawi et al., 2022), and the importance of social banking during crises (Thongsri and Tripak, 2024). This research gap in dynamic modeling of AI's impact on social banking, particularly in cooperative banks, motivates the present study's system dynamics approach.

2.7. Dynamic hypothesis

Building upon the literature review and drawing from expert panel insights, this research develops a comprehensive dynamic hypothesis that articulates the core feedback mechanisms driving AI adoption and performance in social banking systems.

2.7.1. Core dynamic hypothesis

The implementation of AI technologies in social banking creates interconnected reinforcing feedback loops where enhanced AI infrastructure capabilities improve risk assessment accuracy and customer service personalization, leading to increased customer satisfaction and trust. This enhanced reputation enables better resource mobilization and liquidity management, which provides additional capital for further AI investments, creating a virtuous cycle of sustainable development.

2.7.2. Key feedback mechanisms

Reinforcing loop 1 - AI Infrastructure enhancement cycle: AI infrastructure investment → Improved predictive analytics → Enhanced customer satisfaction → Increased bank reputation → Better resource access → Additional AI investment

Reinforcing loop 2 - Risk management optimization cycle: AI-powered risk assessment → Reduced non-performing loans → Improved liquidity stability → Enhanced financial performance → Resources for advanced AI systems → Superior risk management capabilities

Balancing loop 1 - Resource allocation constraints: Increased AI investment demand → Resource competition → Budget limitations → Delayed AI implementations → Temporary performance gaps

This dynamic hypothesis acknowledges that AI adoption in social banking is not a linear process, but rather involves complex interdependencies where system elements both influence and are influenced by one another over time. The hypothesis specifically addresses why some banks achieve sustainable AI-driven transformation while others struggle with implementation challenges.

The temporal dimension is crucial, as the benefits of AI investments may not be immediately apparent but unfold through cascading effects across multiple system components. Understanding these dynamics is essential for developing effective implementation strategies and managing stakeholder expectations during the transformation process.

3. Methodology

This research follows the systematic approach to system dynamics modelling established by [Sterman \(2000\)](#), progressing through five key stages: problem articulation, dynamic hypothesis formation, model building, testing, and policy design.

Error! Reference source not found. illustrates the comprehensive research methodology flowchart that guided this study, showing the systematic progression from problem identification through model validation and scenario analysis.

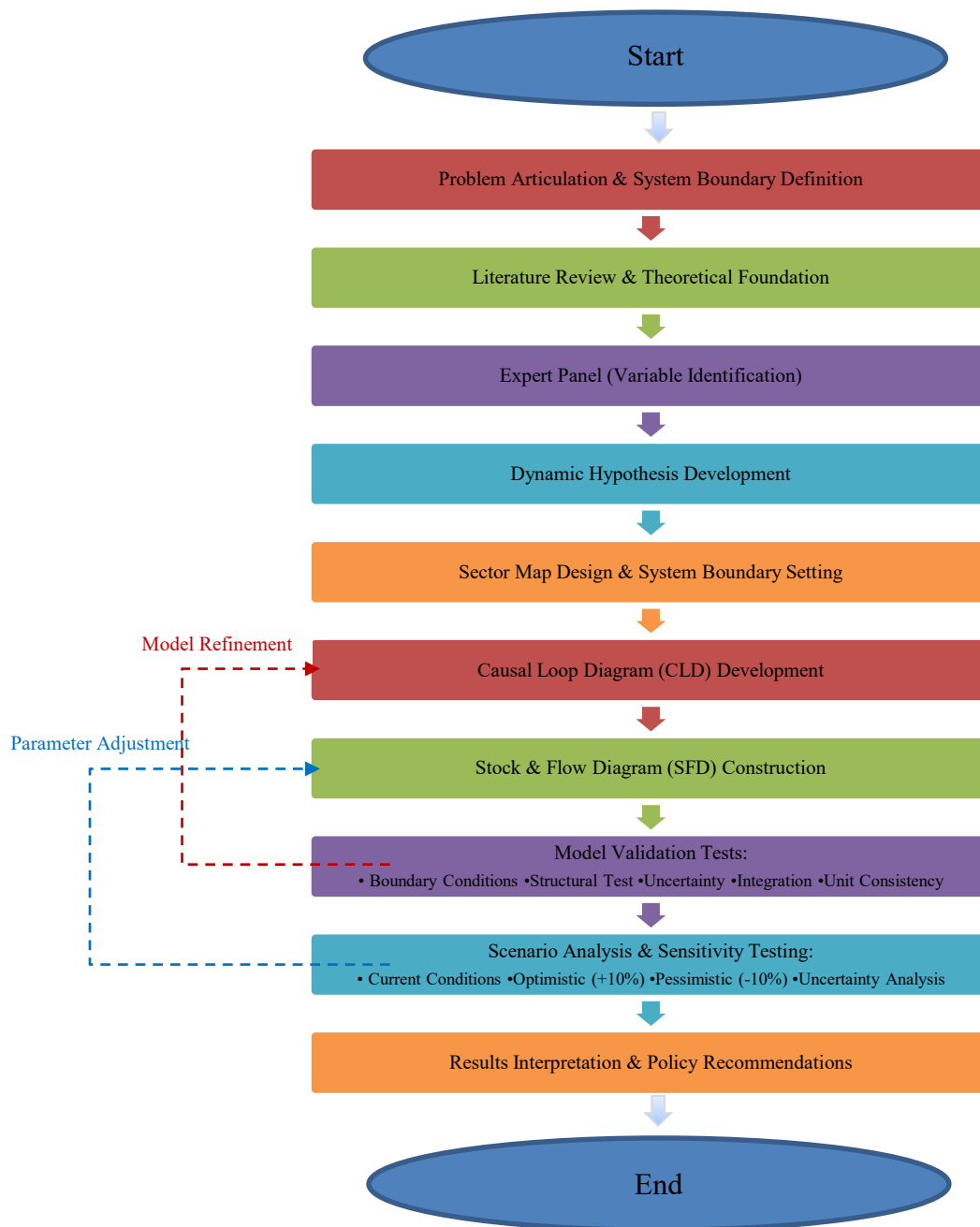


Figure 1. Research methodology flowchart

3.1. Stage 1: Problem articulation and system boundary definition

The first stage involved defining the core problem: understanding how the implementation of AI creates complex feedback effects in social banking systems, particularly within Iranian cooperative banks. System boundaries were established to include: (1) internal bank operations and AI infrastructure, (2) customer interactions and satisfaction mechanisms, (3) financial

performance indicators, and (4) broader sustainability outcomes. External factors such as regulatory changes and macroeconomic conditions were treated as boundary conditions.

3.2. Stage 2: Dynamic hypothesis development

Building on a literature review and preliminary expert consultation, we formulated a dynamic hypothesis articulating three primary feedback loops that drive AI adoption in social banking: infrastructure enhancement cycles, risk management optimization cycles, and resource allocation constraint cycles (detailed in Section 2.7).

3.3. Stage 3: Model building

3.3.1. Phase 3a: Expert panel for variable identification

Using purposive sampling, 15 specialists were selected based on: mastery of cooperative banking concepts, familiarity with AI applications, a minimum master's degree, and 15+ years of senior management experience. The panel consisted of 8 doctoral and seven master's degree holders with diverse expertise (6 with 15-20 years, 5 with 21-25 years, 4 with 25+ years). Three structured panel sessions were conducted using thematic analysis.

3.3.2. Phase 3b: Model structure development

Based on expert panel results and dynamic hypothesis, we developed:

- Sector Map: Defining system boundaries and high-level structure
- Causal Loop Diagrams: Representing feedback loop structures
- Stock and Flow Diagram: Specifying accumulations and rates using Vensim software

3.3.3. Phase 3c: Model formulation

Mathematical equations were formulated for each relationship, with parameters determined through literature review, expert judgment, and available Iranian banking data (2019-2021). The model simulates system behavior over a 10-year period (2021-2031).

3.4. Stage 4: Model testing and validation

Comprehensive validation following SD best practices:

- Structure Testing: Boundary conditions, dimensional consistency, extreme conditions
- Behavior Testing: Integration test, uncertainty analysis (200 Monte Carlo runs)
- Policy Testing: Sensitivity analysis and leverage point identification

3.5. Stage 5: Scenario design and policy analysis

Three scenarios were developed following a $\pm 10\%$ parameter variation approach:

- Current Conditions: Baseline trajectory analysis
- Optimistic Scenario: Enhanced AI investment and improved operational parameters
- Pessimistic Scenario: Reduced capabilities and increased constraints

The $\pm 10\%$ range was selected based on established uncertainty analysis practices in system dynamics modeling (Sterman, 2000) and represents a conservative approach suitable for exploratory analysis in the absence of precise uncertainty distributions. This range provides sufficient sensitivity testing while avoiding extreme conditions that might not reflect realistic operational constraints in the Iranian banking context.

All analyses were performed using Vensim PLE software, with results interpreted through the lens of sustainable banking transformation and policy implications for cooperative banks.

4. Findings

4.1. Causal-Loop diagram analysis

Before presenting the detailed causal loop diagram, **Error! Reference source not found.** shows the sector map of the AI-enabled social banking model, which provides a conceptual framework identifying the main system boundaries and interactions between different sectors.

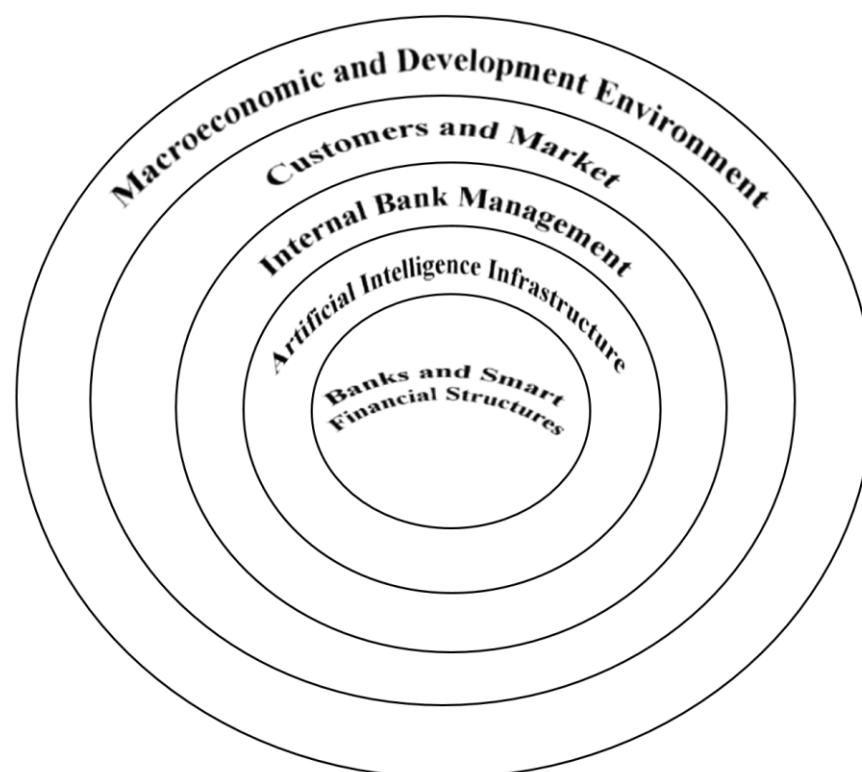


Figure 2. Sector map of AI-enabled social banking model

The sector map illustrates the layered structure of the banking system, with the intelligent banking infrastructure at its core, surrounded by an AI infrastructure layer, internal bank management, customers, and market environment, and the broader economic and development context. This mapping helps define model boundaries and focus analytical attention on key leverage points for improving bank performance.

Based on the results of the expert panel and the system boundaries identified in the sector map, three primary reinforcing feedback loops were identified that drive the behavior of AI-enabled social banking systems. These loops are presented in Figures 3, 4, and 5.

4.1.1. Loop R1: Sustainable development enhancement loop

This primary reinforcing loop demonstrates how AI infrastructure investments create a virtuous cycle of sustainable development. As shown in **Error! Reference source not found.**, enhanced AI capabilities lead to improved service quality and personalization, which increases customer satisfaction and enhances bank reputation, ultimately providing greater resources for additional AI infrastructure investment.

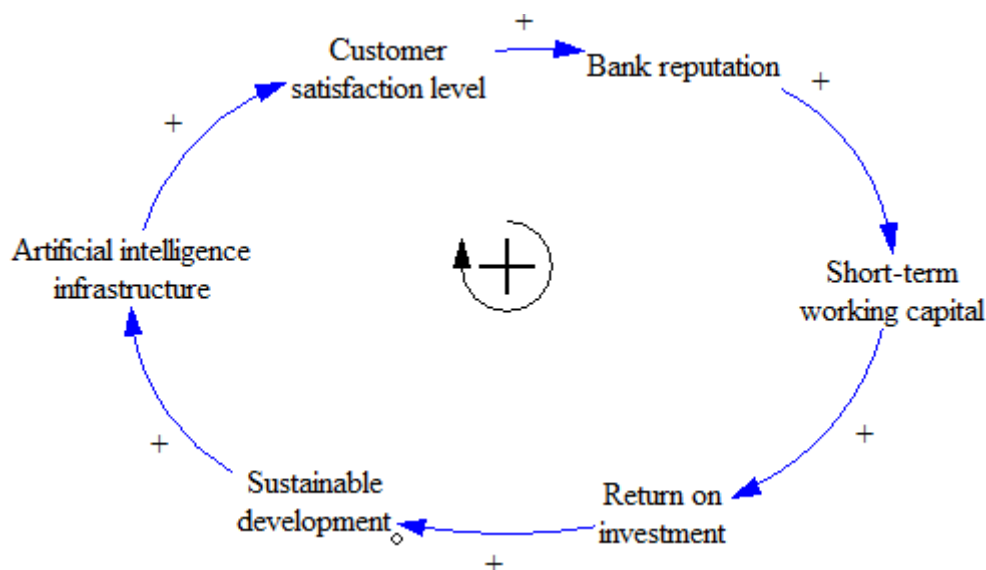


Figure 3. AI infrastructure enhancement loop in social banking

4.1.2. Loop R2: Liquidity optimization loop

Error! Reference source not found. illustrates the dynamic relationship between AI-powered predictive capabilities and liquidity management. AI-based predictive systems enhance liquidity forecasting, reduce unpredictable liquidity fluctuations, improve operational stability, and facilitate better resource allocation for the deployment of advanced AI systems.

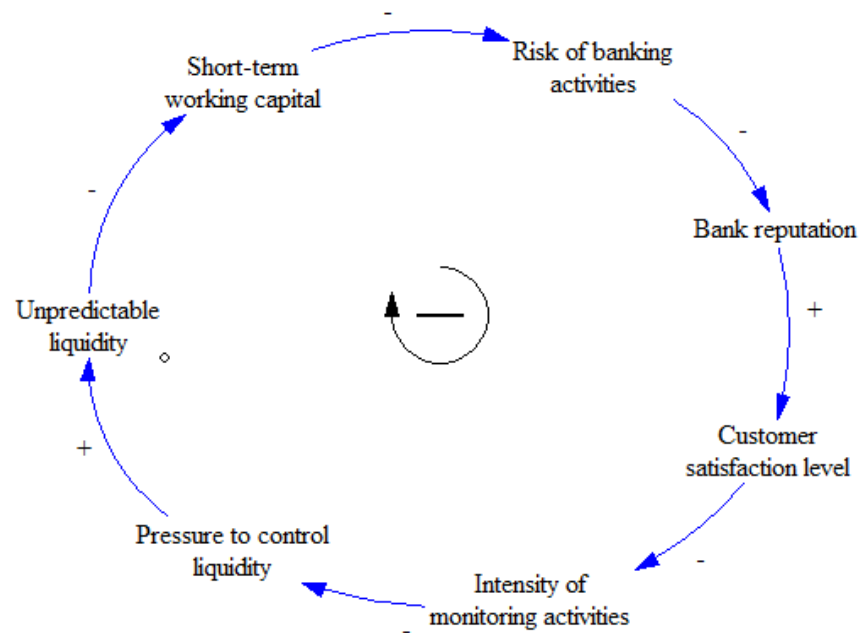


Figure 4. Liquidity management optimization loop through AI

4.1.3. Loop R3: Risk management excellence loop

As depicted in **Error! Reference source not found.**, this reinforcing loop captures how AI capabilities transform credit risk management. Advanced AI algorithms enhance credit risk assessment, reduce non-performing loans, improve financial performance, and increase investment capacity, thereby enabling more sophisticated AI risk management tools.

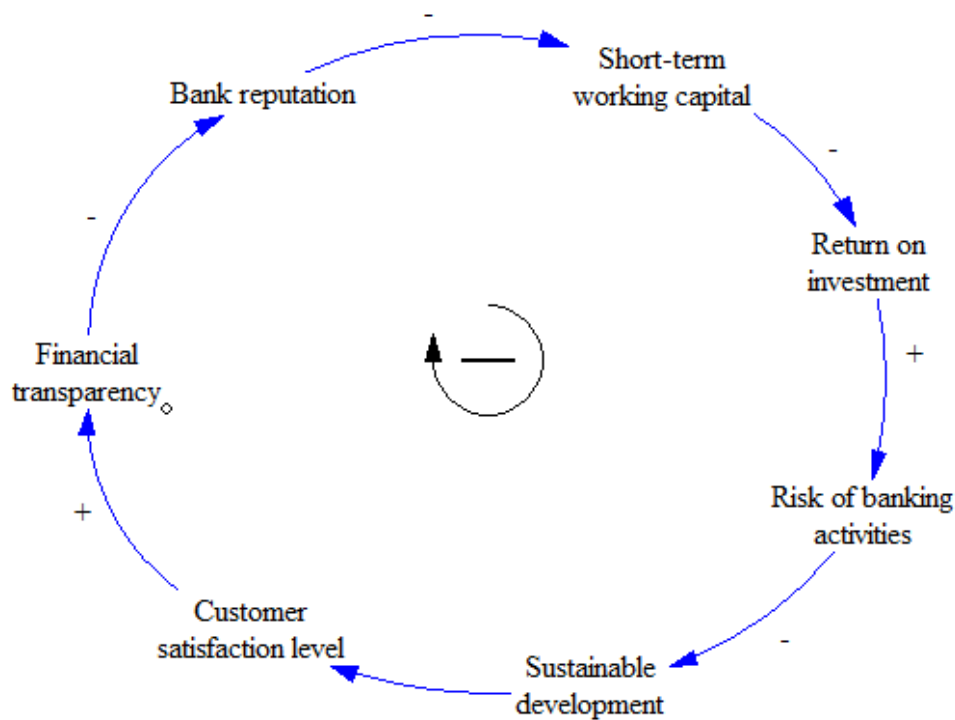


Figure 5. AI-Enabled risk management enhancement loop

These interconnected loops operate simultaneously, with their interactions determining the overall system's behavior. The visual representation in Figures 3-5 clearly demonstrates how each loop reinforces the others, creating either virtuous cycles of improvement or potential challenges when implementation faces obstacles.

4.1.4. Endogenous system dynamics

The three feedback loops presented represent the core endogenous structure of the AI-enabled social banking system. While certain boundary variables (such as regulatory complexity, financial crises, and infrastructure budget) remain exogenous to maintain realistic model boundaries, the primary system behavior emerges from internal interactions between AI infrastructure, customer satisfaction, bank reputation, and financial performance. This endogenous structure accounts for the dominant system dynamics, with exogenous variables serving as necessary boundary conditions rather than primary drivers of system behavior. The focus on these three reinforcing loops demonstrates how internal feedback mechanisms create either virtuous cycles of AI-enabled improvement or implementation challenges, independent of external forcing functions.

4.2. Stock-Flow diagram

Based on the causal-loop diagram, the stock-flow diagram of the model was designed using Vensim software. **Error! Reference source not found.** shows the diagram in which stock variables (including bank reputation, unpredictable liquidity, and non-performing loans) and flow variables (including rates of increase and decrease for each stock variable) are specified.

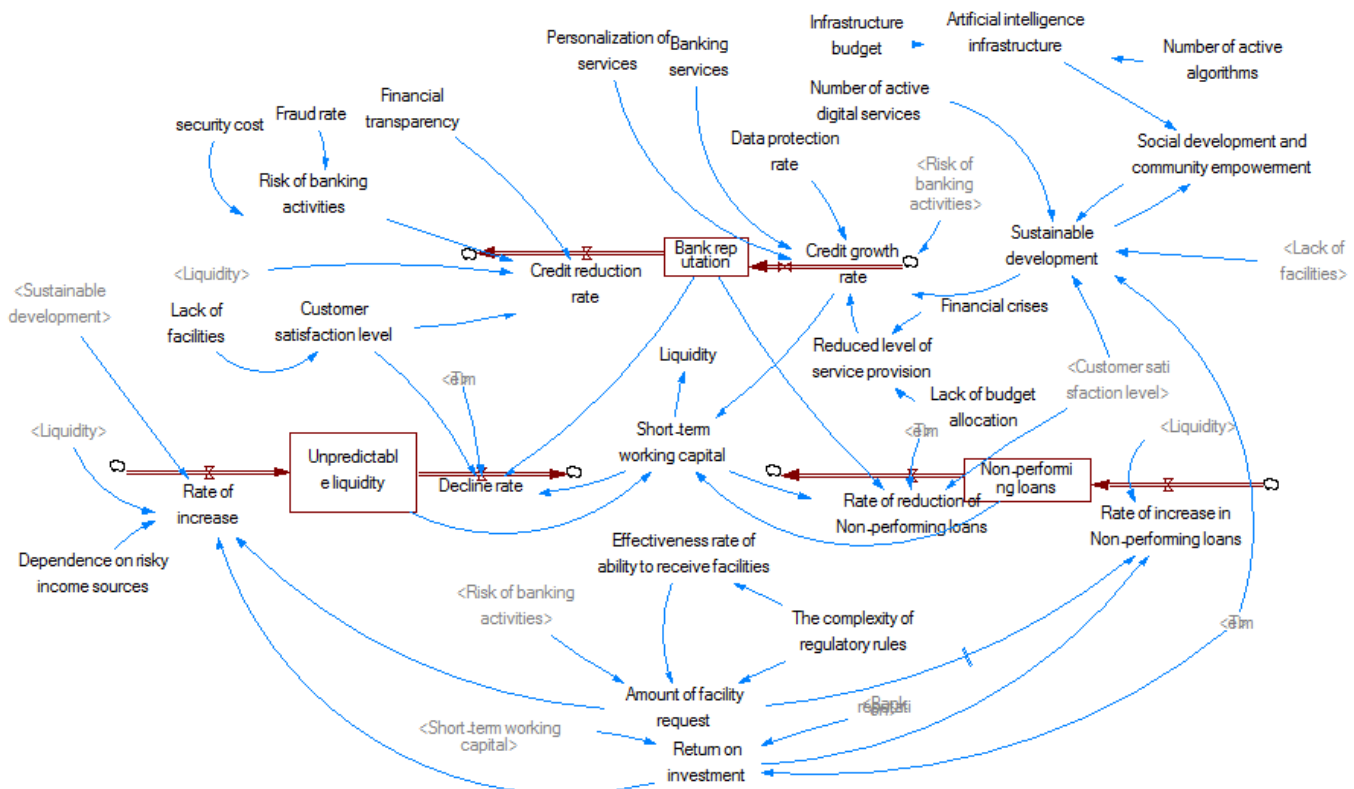


Figure 6. Stock-flow diagram of AI functions in the social banking model

The Time variable appears in the SFD for computational and integration purposes within the Vensim modeling environment, but it does not represent a substantive model component that affects system behavior. This technical variable enables proper equation processing and simulation timing without influencing the core banking dynamics analyzed in this study.

In this model, 31 key variables were identified, and mathematical relationships between them were defined. **Error! Reference source not found.** shows the components in the model.

Table 1. Components in the stock-flow model

Category	Main variables
Stock variables	Bank reputation, Unpredictable liquidity, Non-performing loans
Flow variables	Rate of reputation increase, Rate of reputation decrease, Rate of unpredictable liquidity increase, Rate of unpredictable liquidity decrease, Rate of non-performing loans increase, Rate of non-performing loans decrease
AI-related auxiliary variables	AI infrastructure, Number of active algorithms, Infrastructure budget, Service personalization, Data protection rate
Financial auxiliary variables	Short-term working capital, Return on capital, Liquidity, Financial transparency, Banking activity risk
Operational auxiliary variables	Banking services, Number of active digital services, Customer satisfaction level, Loan denial, Loan application rate
Environmental auxiliary variables	Sustainable development, Social development and community empowerment, Financial crises, Regulatory complexity, Dependency on high-risk revenue sources

Error! Reference source not found. also shows the formulas and relationships used in the model that specify how each variable is calculated.

Table 2. Mathematical equations of key model variables

	Equation	Description	Source
Core System Equations (Standardized Mathematical Notation)	1. Reputation Enhancement Flow $REF = (SD \times BS \times k_1 \times DPR \times SP) / (BAR \times SRL)$	SD = Sustainable development index BS = Banking services portfolio k_1 = Scaling constant (1000) DPR = Data protection rate SP = Service personalization level BAR = Banking activity risk SRL = Service reduction level	Developed through expert panel consensus and adapted from organizational reputation literature (Fombrun, 1996; Reputation Institute, 2020)
	2. Bank Reputation (Stock Variable) $BR(t) = BR(t-dt) + (REF - RDF) \times dt$	BR = Bank reputation level REF = Reputation enhancement flow RDF = Reputation deterioration flow dt = Time increment	Standard stock-flow formulation based on system dynamics methodology (Sterman, 2000)
	3. Reputation Deterioration Flow $RDF = (L/k_1) - BAR^{\wedge}((FT + CSL)/k_2)$	L = Liquidity indicator FT = Financial transparency index CSL = Customer satisfaction level k_2 = Normalization constant (10)	Derived from banking reputation studies and expert elicitation (Mishkin, 2019)
	4. Short-term Working Capital $STWC = NPL \times UL \times k_3 \times REF$	NPL = Non-performing loans level UL = Unpredictable liquidity k_3 = Capital efficiency factor (0.1)	Based on financial management principles (Ross et al., 2019) and Iranian banking data analysis
	5. Banking Activity Risk $BAR = SC \times FR \times k_4$	SC = Security cost index FR = Fraud rate k_4 = Risk scaling factor (1.0)	Adapted from credit risk management literature (Saunders and Allen, 2010) and expert panel validation
	6. Customer Satisfaction Level $CSL = 1 - LD$	LD = Loan denial rate	Based on SERVQUAL framework (Parasuraman et al., 1988) adapted for banking context
	7. AI Infrastructure Index $AII = (IB + AAC)/k_5$	IB = Infrastructure budget allocation AAC = Active algorithms count k_5 = Normalization factor (200)	Developed through expert panel and technology adoption literature (Davenport and Ronanki, 2018)
	8. Return on Capital $ROC = \max(0, (STWC/T - BR/T)/k_6)$	T = Time period k_6 = Performance scaling factor (1000)	Standard financial performance metrics (Gitman and Zutter, 2015) adapted for system dynamics context
	9. NPL Recovery Flow $NPLRF = (STWC/T \times CSL) + (BR/T)$	NPLRF = Non-performing loans recovery flow	Based on banking recovery models and expert judgment
	10. Liquidity Stabilization Flow $LSF = (STWC/T \times k_7 \times CSL) - (BR/T)$	LSF = Liquidity stabilization flow k_7 = Processing efficiency factor (100)	Liquidity management literature (Koch and MacDonald, 2014) and expert panel insights
Equation Development Methodology	Literature Synthesis (40%): Core relationships derived from established banking, AI, and system dynamics literature. Expert Elicitation (35%): Three rounds of structured expert panel sessions with 15 banking and AI specialists. Empirical Calibration (25%): Parameter values calibrated using available Iranian banking sector data (2019-2021) from Central Bank of Iran reports. Validation: All equations underwent dimensional analysis and behavioral testing to ensure logical consistency and realistic system behavior.		
Unit Consistency Verification	Dimensional Analysis Results: - All flow variables: [dimensionless units]/Time - All stock variables: [dimensionless units] - All ratios and indices: Properly normalized (0-100 scale) - All constants: Dimensionally consistent with their applications Verification Process: Comprehensive unit checking performed using Vensim PLE built-in dimensional analysis tools. No dimensional errors detected in the final model structure.		

4.2.1. Parameter sources and validation

All model parameters were carefully calibrated using a combination of available banking sector data, expert judgment, and literature-based estimates. To maintain consistency and enable cross-variable comparison, all components were normalized to a 0-100 scale representing percentage values.

Table 3. Parameter constants table

Parameter	Value	Definition	Source
k ₁	1000	Reputation scaling constant	Calibrated through expert panel
k ₂	10	Transparency normalization factor	Based on banking disclosure standards
k ₃	0.1	Capital efficiency factor	Iranian banking sector analysis
k ₄	1.0	Risk scaling factor	Risk management literature
k ₅	200	AI infrastructure normalization	Technology adoption studies
k ₆	1000	Performance scaling factor	Financial analysis standards
k ₇	100	Processing efficiency factor	Operational research literature

4.2.2. Key parameter sources

To develop the model, a set of key parameters was identified and initially calibrated. These parameters were derived from reputable academic sources, official data, and prior studies in the fields of banking and technology, as outlined below:

- Return on Capital: Based on Central Bank of Iran reports (2019-2021) and banking performance studies ([Amiri et al., 2022](#))
- Banking Activity Risk: Derived from credit risk assessment literature ([Saunders and Allen, 2010](#)) and Iranian banking risk studies ([Masoudi, 2021](#))
- Bank Credibility: Calibrated using customer trust surveys and reputation indices ([Mishkin, 2019](#))
- Customer Satisfaction: Based on SERVQUAL measurement scales ([Parasuraman et al., 1988](#)) adapted for the Iranian banking context
- Financial Transparency: Derived from banking disclosure standards ([Bushman and Smith, 2001](#))
- AI Infrastructure: Based on technology adoption frameworks in banking ([Gyau et al., 2024](#))

4.2.3. Fixed parameter rationale

Several variables were held constant during the simulation period due to their relatively stable nature in the short to medium term or their limited direct impact on core system dynamics. This simplification approach is consistent with system dynamics modelling best practices, where the focus is on understanding behavioural patterns rather than precise numerical predictions.

Table 4. Fixed parameter values

Variable	Value	Rationale	Variable
Active digital services	10	Based on a typical cooperative bank service portfolio	Active digital services
Active algorithms count	13	Representative of current AI implementation in Iranian banks	Active algorithms count
Infrastructure budget	12	Normalized value based on sector averages	Infrastructure budget
Security cost	400,000	Based on cybersecurity investment studies	Security cost
Financial crises impact	0.8	Historical crisis impact analysis	Financial crises impact
Loan denial rate	0.8	Iranian cooperative banking sector data	Loan denial rate
Regulatory complexity	0.25	Banking regulation complexity index	Regulatory complexity
Service personalization	25	Current personalization capability assessment	Service personalization
Data protection rate	45	Current data security implementation level	Data protection rate
Fraud rate	17	Banking fraud statistics (Central Bank of Iran)	Fraud rate
High-risk revenue dependency	1.05	Risk exposure assessment	High-risk revenue dependency

4.2.4. Qualitative variable scale definitions

All qualitative variables are normalized to a 0-100 percentage scale with the following interpretation framework:

- Bank Reputation: 0-33 (Poor reputation, limited market trust), 34-66 (Moderate reputation, average market standing), 67-100 (Strong reputation, high market confidence)
- Customer Satisfaction Level: 0-33 (Low satisfaction, frequent complaints), 34-66 (Moderate satisfaction, acceptable service), 67-100 (High satisfaction, loyal customer base)
- Financial Transparency: 0-33 (Limited disclosure, opacity in reporting), 34-66 (Standard disclosure, regulatory compliance), 67-100 (Full transparency, proactive disclosure)
- Service Personalization: 0-33 (Generic services, no customization), 34-66 (Limited personalization, basic customization), 67-100 (Highly personalized, AI-driven customization)
- Data Protection Rate: 0-33 (Basic security, minimal protection), 34-66 (Standard security, regulatory compliance), 67-100 (Advanced security, comprehensive protection)

These scales enable consistent interpretation of qualitative improvements and facilitate meaningful comparison across different model scenarios.

4.2.5. Unit consistency verification

Comprehensive unit consistency checks were performed using Vensim's built-in validation tools. All equations maintain dimensional consistency, with percentage-based variables

properly scaled and normalized to prevent computational errors.

4.3. Model validation

To ensure the validity of the designed model, multiple tests were conducted. The results of these tests are as follows.

4.3.1. Boundary conditions test

In this test, system behaviour at extreme values of variables was examined. Figure 7 shows the behaviour of essential model components at extreme points.

The results show that when the "data protection rate" variable is at an extreme point, non-performing loans and unpredictable liquidity reach their minimum possible value, which improves the bank's reputation component.

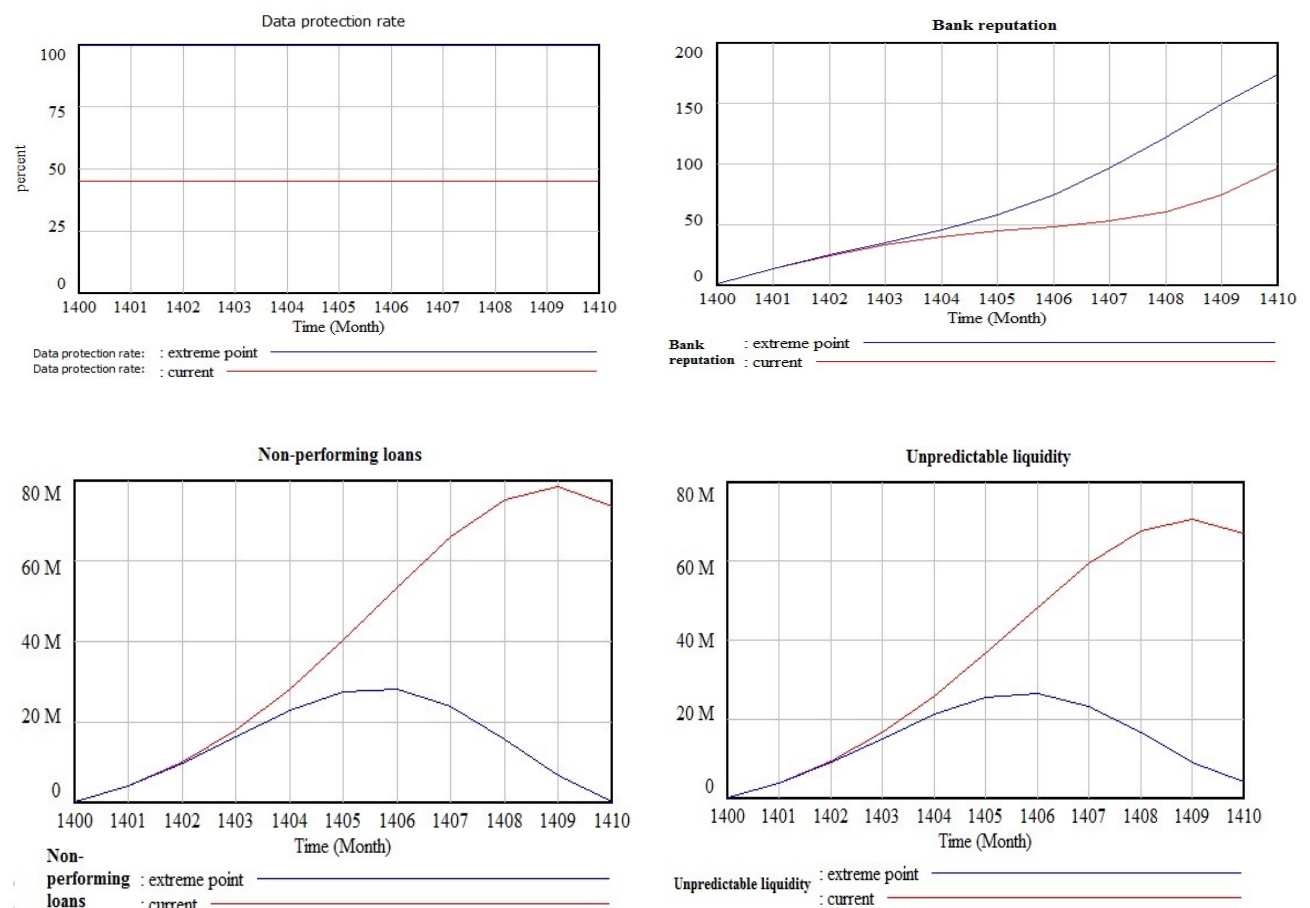


Figure 7. Reaction of main model components under boundary conditions

4.3.2. Structural test of the model

The results of the structural test show that the presented model is free of any structural errors and the defined variables are consistent with each other, as shown in Figure 8.

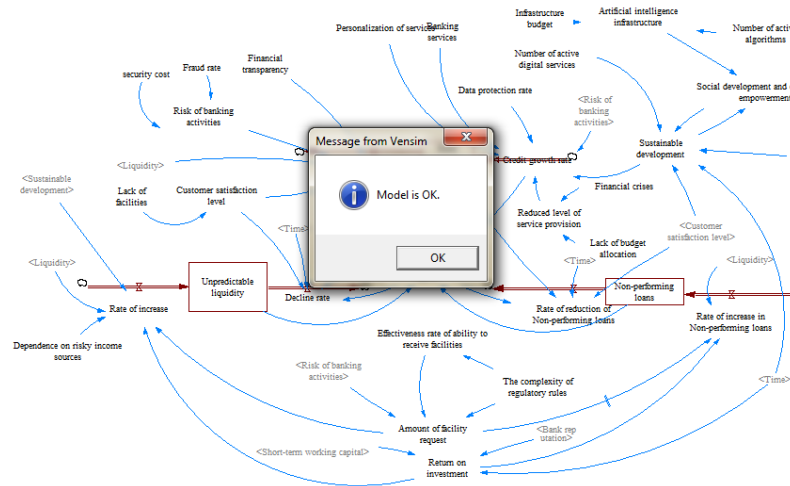


Figure 8. Confirmation of model structural correctness by Vensim software

4.3.3. Uncertainty test

In this test, the model was simulated 200 times with different input parameter values. Figure 9 shows the behaviour of the "unpredictable liquidity," "non-performing loans," and "bank reputation" components under uncertainty.

The results indicate that the yellow areas have the highest probability of occurrence, while the grey areas have the lowest probability of occurrence. Since the set of specified areas is within the approved range and no area outside the expected limit has formed, this indicates the existence of healthy relationships and behaviour among parameters and components.

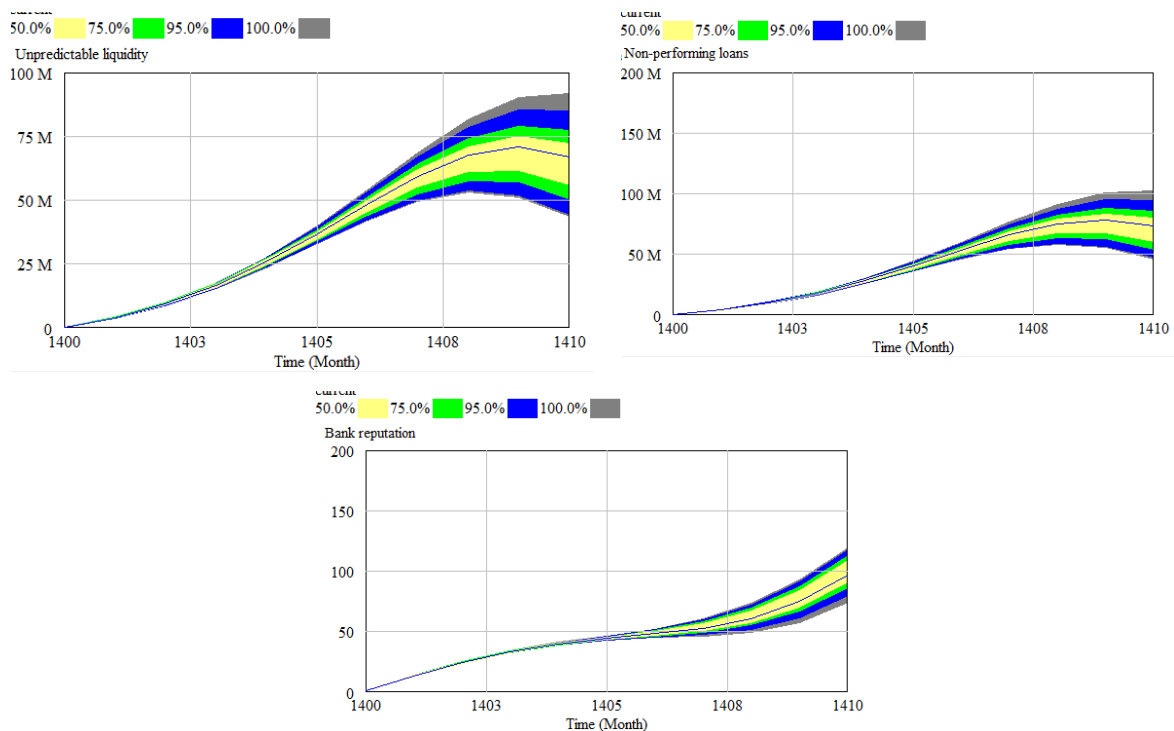


Figure 9. Uncertainty analysis of main model variables

4.3.4. Integration test

The results of the integration test, as presented in Figure 10, show that reducing the time step does not change the behavior of the graphs, and no value outside of the larger time steps is observed.

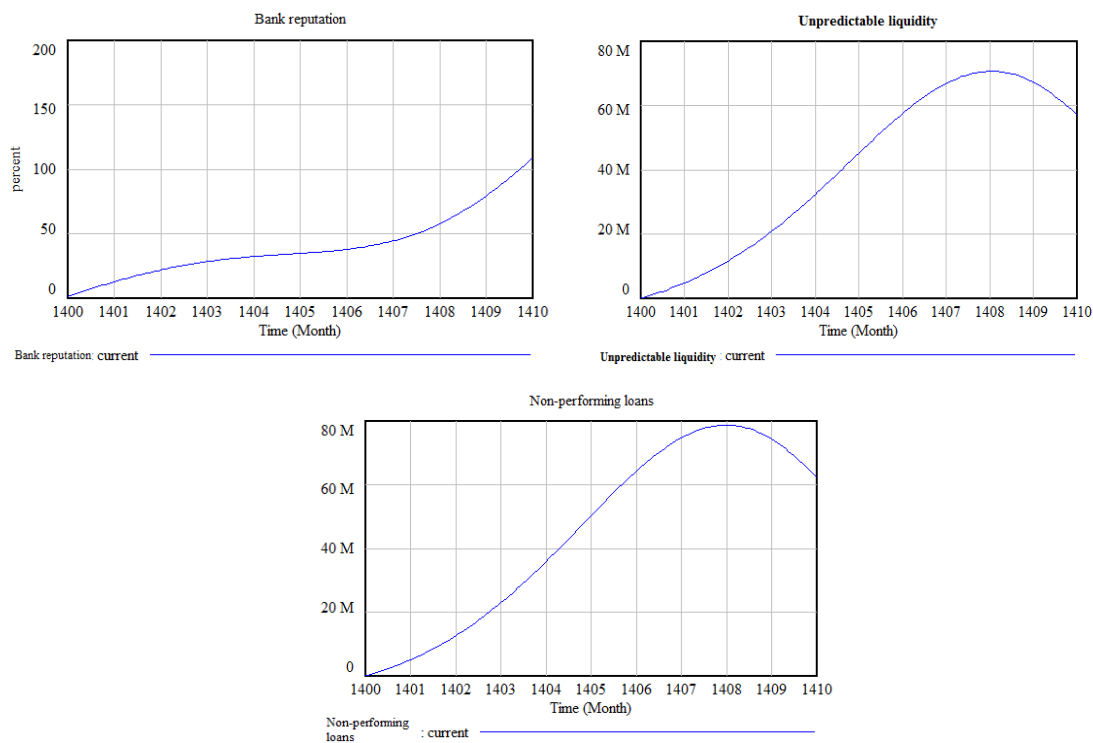


Figure 10. Model stability in different time steps

4.3.5. Leverage points test

In this test, variables that have the greatest impact on the main component were identified. The results in Figure 11 show that with a 10% increase in "service personalization," bank reputation has had a significant growth at the end of the period of interest.

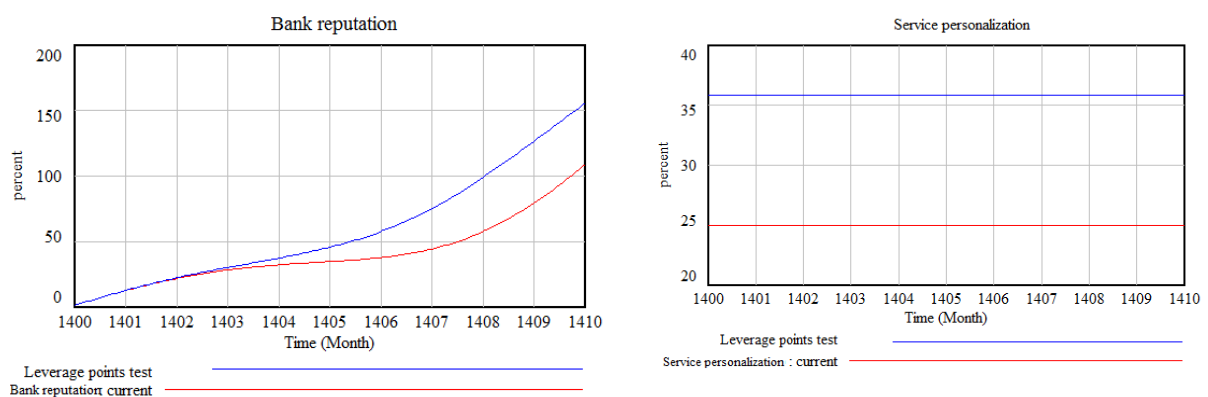


Figure 11. Effect of leverage variables on bank reputation

4.4. Scenario analysis

4.4.1. Current conditions continuation scenario

In this scenario, system behaviour was examined without changing the current trend. **Error! Reference source not found.** shows the behaviour of "unpredictable liquidity," "non-performing loans," and "bank reputation" components in normal conditions.

The results show that in this scenario:

1. Unpredictable liquidity has an upward trend from 2021 to 2028, reaching about 80 million units, and then decreases.
2. Non-performing loans also follow a trend similar to unpredictable liquidity.
3. Bank reputation has an upward trend from the beginning to the end of the period.

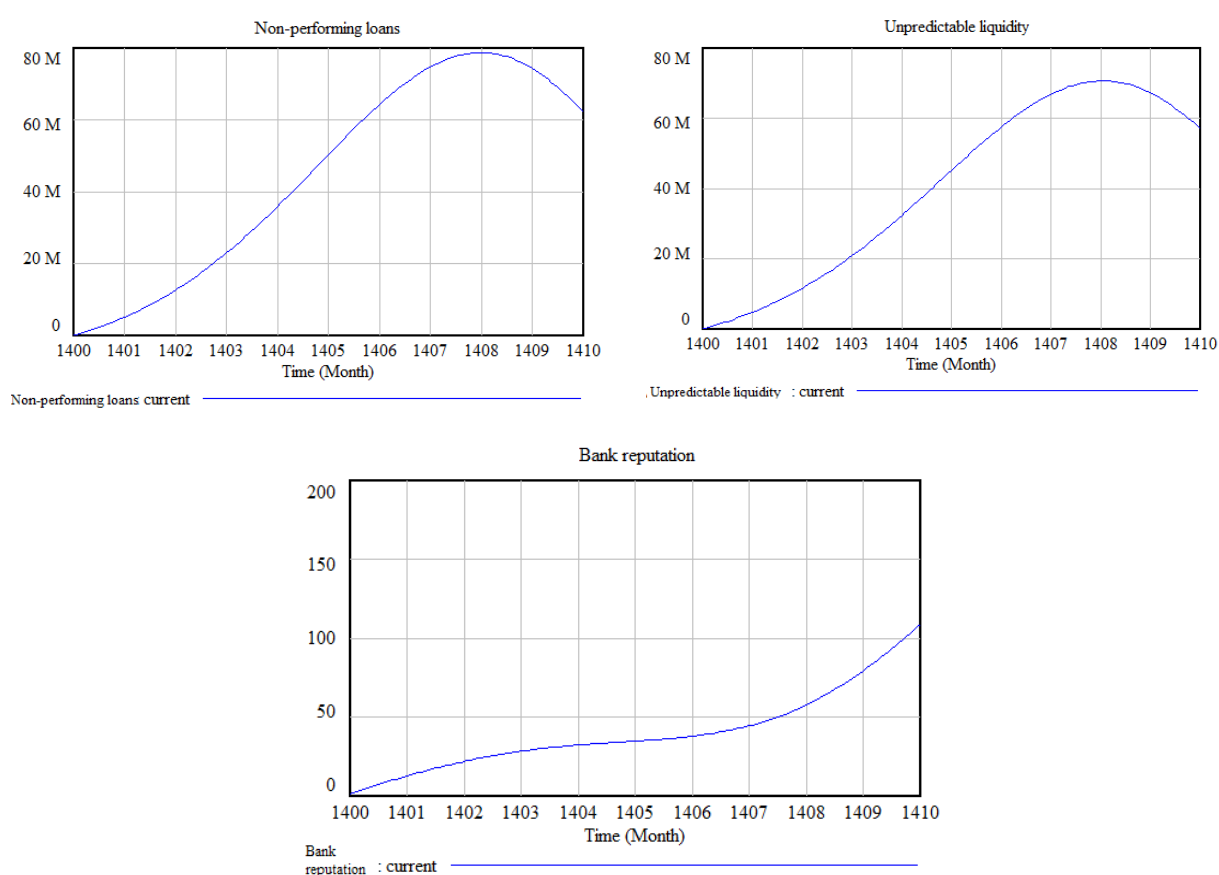


Figure 12. Trend of main model variables in the current conditions continuation scenario

4.4.2. Optimistic-Pessimistic scenario

In this scenario, model behaviour was examined with a 10% change in influencing factors. Figure 13 shows model behaviour under the optimistic-pessimistic scenario.

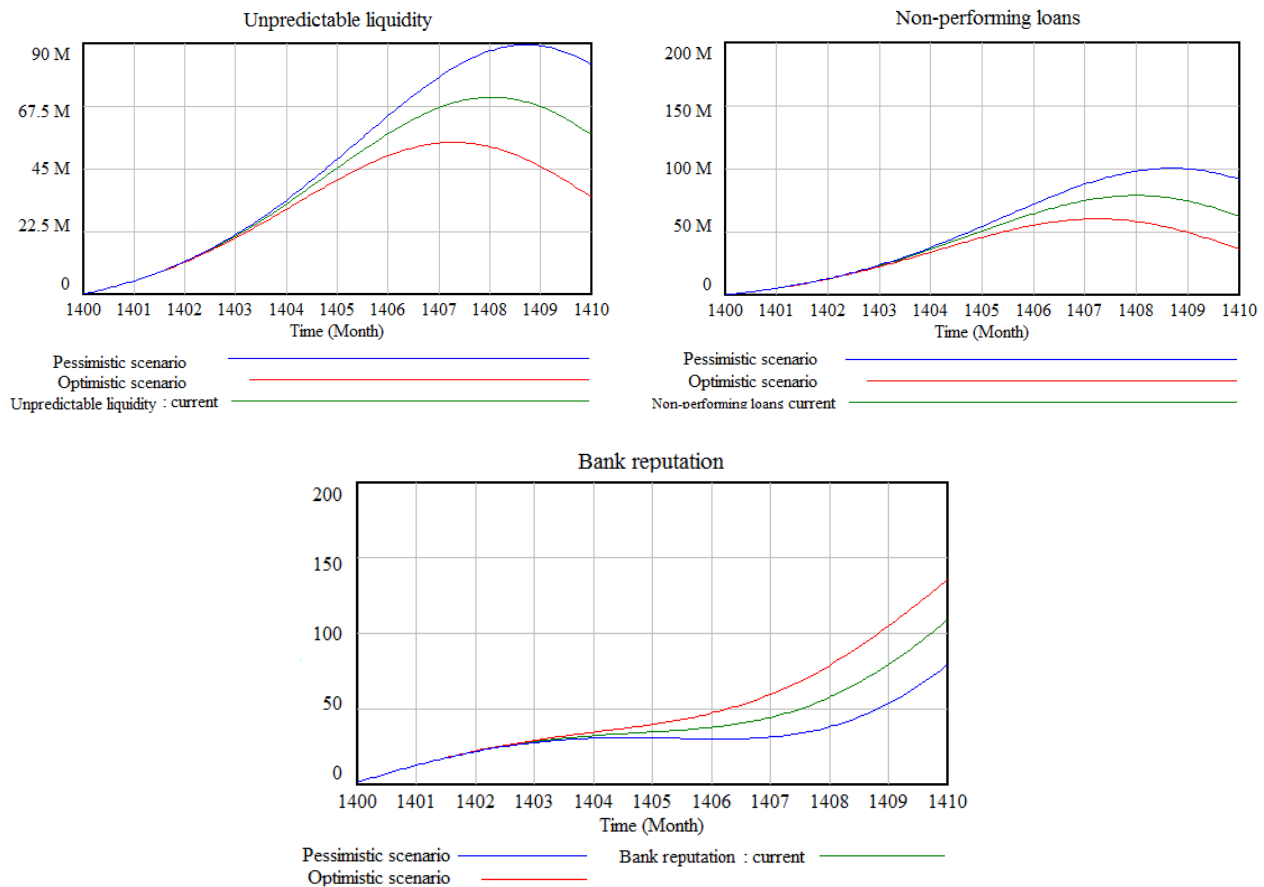


Figure 13. Comparison of optimistic and pessimistic scenarios for key variables

Tables 5, 6, and 7 present parameter changes related to the variables of "unpredictable liquidity," "non-performing loans," and "bank reputation" under the influence of the optimistic-pessimistic scenario.

Table 5. Parameter changes related to "unpredictable liquidity" under the influence of an optimistic-pessimistic scenario

Unpredictable liquidity	Optimistic state	Pessimistic state
Dependency on high-risk revenue sources	10% decrease	10% increase
Loan denial	10% decrease	10% increase

Table 6. Parameter changes related to "non-performing loans" under the influence of an optimistic-pessimistic scenario

Non-performing loans	Optimistic state	Pessimistic state
Budget non-allocation	10% decrease	10% increase
Financial crises	10% decrease	10% increase

Table 7. Parameter changes related to "bank reputation" under the influence of an optimistic-pessimistic scenario

Bank reputation	Optimistic state	Pessimistic state
Data protection rate	10% increase	10% decrease
Financial transparency	10% increase	10% decrease

Scenario design and interpretation framework:

For qualitative variables in this study, the $\pm 10\%$ changes represent realistic operational adjustments rather than precise quantitative shifts:

- **Data protection rate ($\pm 10\%$):** Represents implementation of enhanced/reduced cybersecurity protocols and data governance measures
- **Financial transparency ($\pm 10\%$):** Reflects increased/decreased disclosure practices and reporting frequency
- **Loan denial rate ($\pm 10\%$):** Indicates tightened/relaxed credit approval criteria
- **Service personalization ($\pm 10\%$):** Represents enhanced/reduced AI-driven customer service customization

Outcome interpretability:

Given the normalized 0-100 scale for all variables, outcomes should be interpreted as relative performance indicators rather than absolute measures. For instance, "bank reputation increase" indicates improved relative standing compared to baseline conditions, while the magnitude reflects the strength of improvement within the modelled system constraints.

The results show that:

- (1) In the optimistic scenario, unpredictable liquidity decreases to 34 million (compared to 57 million in the baseline scenario), while in the pessimistic scenario, it increases to 82 million.
- (1) In the optimistic scenario, non-performing loans reach 32 million (compared to 60 million in the baseline state), while in the pessimistic scenario, they increase to 90 million.
- (2) In the optimistic scenario, bank reputation increases by 20%, while in the pessimistic scenario, it decreases by 20%.

4.4.3. Optimistic-Pessimistic scenario under uncertainty

Figure 14 shows the behaviour of the bank reputation component under uncertainty.

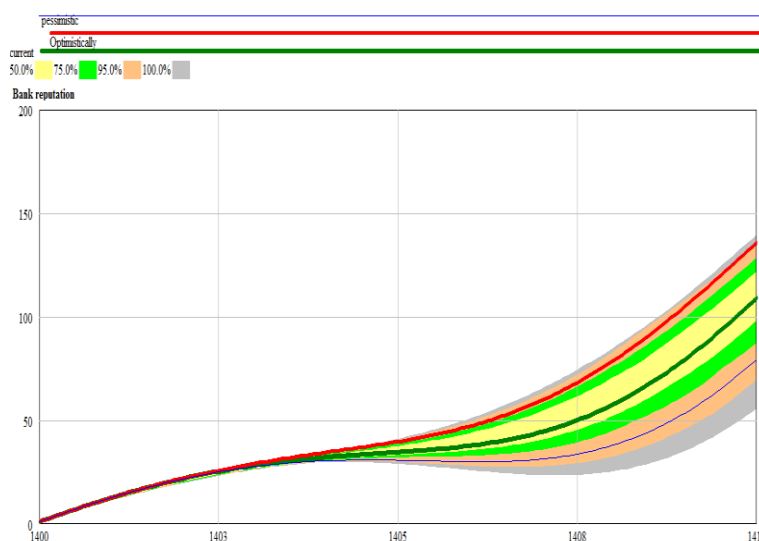


Figure 14. Probability of occurrence of different scenarios for bank reputation

The results show that the likelihood of the bank reputation component being in the pessimistic state is higher than in the optimistic state, which indicates insufficient attention to this topic and the need for addressing it to prevent a decrease and taking measures to increase the value of this component. Table 8 shows the level of uncertainty in different states of the bank reputation component.

Table 8. Confidence levels for different scenarios of bank reputation

Capital lockup	Uncertainty: 100	Uncertainty: 95	Uncertainty: 75	Uncertainty: 50
Optimistic state	✓			
Normal state				✓
Pessimistic state		✓		

5. Discussion and conclusion

This research was conducted to study the impact of AI functions on social banking performance using a system dynamics approach in Iranian cooperative banks. The results from modelling and simulation indicate the significant impact of AI infrastructure on key variables of the social banking system. In this section, the research findings are discussed and compared with the results of previous studies. Next, the practical and theoretical applications of the research, its limitations, and suggestions for future studies are presented.

The research results demonstrated that strategic investments in AI infrastructure, coupled with enhanced data protection protocols and improved financial transparency, generate substantial improvements across key performance indicators. The modelling analysis revealed significant positive impacts on bank reputation, marked reductions in unpredictable liquidity fluctuations, and notable decreases in non-performing loans, supporting the hypothesis that AI-enabled social banking can achieve sustainable operational excellence. These findings are consistent with previous studies on the impact of AI on improving risk management and liquidity ([Fourie and Bennett, 2019](#); [Sadok et al., 2022](#)).

Analysis of the causal-loop diagram showed that three main cycles could be identified in the AI functions in social banking model: the cycle of relationship between sustainable development, bank reputation, liquidity, and short-term working capital; the cycle of interaction between liquidity, unpredictable liquidity, and short-term working capital; and the cycle of relationship between liquidity, non-performing loans, and short-term working capital. These cycles demonstrate the complexity of relationships between key system variables and are consistent with previous studies on banking system dynamics ([Al-Sartawi et al., 2022](#)).

Scenario analysis indicated that if current conditions persist, unpredictable liquidity and non-performing loans will exhibit an upward trend, but after reaching a peak, they are expected to

decline. This behavioural pattern could be due to corrective actions and control policies that are adopted after experiencing crisis conditions. This finding is consistent with the results of [Thongsri and Tripak's \(2024\)](#) study, which showed that social banks take effective measures for liquidity and risk management in crisis conditions.

A comparison of optimistic and pessimistic scenarios revealed that relatively small changes (10%) in key parameters can have a significant impact on system behavior. This finding demonstrates the system's sensitivity to changes and the importance of strategic decisions regarding the application of AI. [Venanzi and Matteucci \(2022\)](#) also highlighted the importance of strategic decisions in the sustainability of cooperative banks in their study.

Uncertainty analysis showed that the probability of the bank reputation component being in the pessimistic state is higher than in the optimistic state. This finding highlights the need for increased attention to factors influencing bank reputation and the adoption of effective policies for risk management in this area. [Korzeb et al.'s \(2024\)](#) study also emphasized the importance of risk management and maintaining reputation in cooperative banks.

From a theoretical perspective, this research adds to the existing literature on social banking and applications of AI in banking. The presented dynamic model provides a conceptual framework for understanding complex interactions between key variables of the AI functions in the social banking system. This model can serve as a basis for future research in this field.

From a practical perspective, the results of this research can serve as a useful guide for cooperative bank managers when considering investment in AI technologies. The presented model enables simulation of different scenarios and helps managers predict the consequences of various decisions.

Based on the research findings, several strategies are proposed for improving AI functions in social banking performance. Investment in AI infrastructure is a fundamental priority that includes developing the necessary infrastructure for implementing intelligent systems, encompassing hardware, software, and specialized human resources. Additionally, enhancing data security by implementing advanced security protocols to safeguard customer data and mitigate cyber threats is crucial.

Developing data analysis systems using ML algorithms to analyse customer behaviour and provide personalized services is another strategy that can help improve the quality of banking services. Optimizing lending processes through the use of AI models for credit risk assessment and improving the loan-granting process is also of high importance. Finally, increasing financial transparency using modern technologies to enhance transparency in financial transactions can

lead to improved customer trust and strengthen the position of cooperative banks in the country's banking system.

While this study primarily focuses on the economic and social dimensions of AI-enabled banking, we also recognize that comprehensive sustainability requires environmental considerations. Future research should explore how AI technologies in banking can contribute to environmental sustainability through paperless operations, optimized energy consumption in banking facilities, and support for green financing initiatives. The current model provides a foundation that can be extended to incorporate environmental indicators as data availability and measurement frameworks improve in the Iranian banking context.

This research, like any other research, has faced limitations. First, the presented model has been developed based on available data and expert opinions, and may not fully reflect the complexities of the real system. Second, model parameters have been determined based on expert estimates and may require revision as conditions change. Third, this research has focused only on Iranian cooperative banks, and its results may not be generalizable to other types of banks or other countries. The current model does not explicitly incorporate time delays between cause-and-effect relationships, which could provide additional realism in representing the temporal dynamics of AI implementation impacts. Future model iterations should consider incorporating appropriate delay structures based on empirical evidence of AI adoption timelines in banking operations.

To complement and build upon the achievements of this research, several potential research paths for future studies are proposed. Developing the model with real data, using actual bank data for model calibration, can significantly help increase prediction accuracy. Comparing different banks to explore the impact of AI on the performance of various kinds of banks (commercial, specialized, and cooperative) can provide a more comprehensive perspective on the topic.

Examining the role of organizational culture in the successful implementation of AI systems in banks is another important study area that can help better understand human factors affecting this process. Conducting a more detailed analysis of the costs and benefits of investing in AI technologies in cooperative banks can also lead to more effective economic decisions in this area. Finally, developing models with longer time horizons to examine the long-term impacts of AI on bank sustainability and competitiveness can provide a clearer vision of the future of the banking industry.

This research demonstrates that AI can play a significant role in enhancing social banking performance in cooperative banks. Investing in AI infrastructure, enhancing data protection,

and improving financial transparency can increase a bank's reputation, reduce unpredictable liquidity, and lower non-performing loans. The system dynamics model presented in this research provides a framework for understanding complex interactions between key system variables and can be used as a tool for decision-making and policy-making regarding the application of AI in the country's social banking system.

Given the growing trend of digitalization in banking services and the increasing importance of banks' social responsibilities, implementing AI functions in a social banking model can be an important step toward sustainable development, improving financial performance, and increasing customer satisfaction. It requires a commitment from senior management, appropriate investment, and the development of long-term strategies.

Disclosure statement

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

References

- Musleh Al-Sartawi, A.M., Hussainey, K. and Razzaque, A., 2022. The role of artificial intelligence in sustainable finance. *Journal of Sustainable Finance & Investment*, pp.1-6. <https://doi.org/10.1080/20430795.2022.2057405>.
- Al-Sartawi, A.M.M. ed., 2022. *Artificial Intelligence for Sustainable Finance and Sustainable Technology: Proceedings of ICGER 2021* (Vol. 423). Springer Nature. <http://dx.doi.org/10.1007/978-3-030-93464-4>.
- Amiri, M., Radfar, R. and Faezi Razi, F., 2022. Presenting a model of Social Banking effect on reducing the financial conflict between banks and manufacturing firms using the fuzzy Dimatel technique: A study on Resalat Qarz al-Hasana Bank. *Iranian journal of management sciences*, 17(67), pp.27-46.[In Persian].
- Andrikopoulos, A., 2020. Delineating social finance. *International Review of Financial Analysis*, 70, p.101519. <https://doi.org/10.1016/j.irfa.2020.101519>.
- Bushman, R.M. and Smith, A.J., 2001. Financial accounting information and corporate governance. *Journal of accounting and Economics*, 32(1-3), pp.237-333. [https://doi.org/10.1016/S0165-4101\(01\)00027-1](https://doi.org/10.1016/S0165-4101(01)00027-1).
- Castelli, M., Manzoni, L. and Popovič, A., 2016. An artificial intelligence system to predict quality of service in banking organizations. *Computational intelligence and neuroscience*, 2016(1), p.9139380. <https://doi.org/10.1155/2016/9139380>.
- Davenport, T.H. and Ronanki, R., 2018. Artificial intelligence for the real world. *Harvard business review*, 96(1), pp.108-116.
- de Andreis, F., Comite, U., Gallo, A.M., Andone, D.M. and Ciaschi, G., 2024. Social business, artificial intelligence, and sustainability: An integrated approach for the future. *Sustainable Economies*, 2(1), pp.18-18. <https://doi.org/10.62617/se.v2i1.18>.

- Degregori, G., Brescia, V., Calandra, D. and Secinaro, S., 2025. Evaluating sustainability reporting in SMEs: insights from an ethical cooperative bank's approach. *Journal of Global Responsibility*, (ahead-of-print). <https://doi.org/10.1108/JGR-10-2024-0197>.
- Fombrun, C.J., 1996. Reputation: Realizing value from the corporate image. *Harvard Business School*.
- Fourie, L. and Bennett, T., 2019. Super intelligent financial services. *Journal of payments strategy & systems*, 13(2), pp.151-164. <http://dx.doi.org/10.69554/ITYX9650>.
- Gautam, T., Srivastava, A. and Jain, S., 2024. Efficiency evaluation of state cooperative banks employing data envelopment analysis and neural network technique. *International Journal of Business Process Integration and Management*, 11(3), pp.179-185. <https://doi.org/10.1504/IJBPM.2024.140141>.
- Gitman, L.J. and Zutter, C.J., 2015. *Principles of managerial finance*, 14th Edition. Pearson.
- Gyau, E.B., Appiah, M., Gyamfi, B.A., Achie, T. and Naeem, M.A., 2024. Transforming banking: Examining the role of AI technology innovation in boosting banks financial performance. *International Review of Financial Analysis*, 96, p.103700. <https://doi.org/10.1016/j.irfa.2024.103700>.
- Iannaci, D. and Gideon, M.J., 2020. Islamic finance and social finance, an opportunity for social enterprises. *European Journal of Islamic Finance*, 1, pp.1-12. <https://doi.org/10.13135/2421-2172/4242>.
- Jakšič, M. and Marinč, M., 2019. Relationship banking and information technology: The role of artificial intelligence and FinTech. *Risk Management*, 21(1), pp.1-18. <http://dx.doi.org/10.2139/ssrn.3059426>.
- Karki, U., Kumar, A. and Sharma, D., 2025. Banking in sustainability: an integrated MCDM framework for evaluating the environmental, social, and governance (ESG) sustainable banking performance. *Global Knowledge, Memory and Communication*. <https://doi.org/10.1108/GKMC-04-2024-0241>.
- Kil, K., Ciukaj, R. and Chrzanowska, J., 2021. Scoring models and credit risk: The case of cooperative banks in Poland. *Risks*, 9(7), p.132. <https://doi.org/10.3390/risks9070132>.
- Koch TW, MacDonald SS. 2014. *Bank Management*. 8th Edition. South-Western Cengage Learning.
- Korzeb, Z., Niedziółka, P., Szpilko, D. and De la Torre, A., 2024. A bibliometric analysis of ESG performance in the cooperative banks: from the current status to future directions. *Economics and Environment*, 89(2), p. 809. <https://doi.org/10.34659/eis.2024.89.2.809>.
- Masoudi S, Cheshmi A and Razmi SMJ., 2021. An analysis of the impact of financial supervision quality on credit risk in Iranian banks using panel quantile regression. *Journal of Monetary and Banking Research*. 14(48) , pp. 395–420. [In Persian].
- Mishkin, F.S., 2019. *The economics of money, banking, and financial markets*. 12th Edition. Pearson Pearson education.
- Nethala, V.J., Pathan, M.F.I. and Sekhar, M.S.C., 2022. A study on cooperative banks in India with special reference to marketing strategies. *Journal of Contemporary Issues in Business and Government Vol*, 28(04). <https://doi.org/10.47750/cibg.2022.28.04.041>.
- Ozili, P.K., 2025. Financial inclusion in banking: A literature review and future research directions. <https://doi.org/10.61351/mf.v3i1.236>.
- Parasuraman, A.B.L.L., Zeithaml, V.A. and Berry, L., 1988. SERVQUAL: A multiple-item scale for measuring consumer perceptions of service quality. *1988*, 64(1), pp.12-40.

- Pérez, M.E.S., 2017. SEBI index: Measuring the commitment to the principles of social banking. *Contaduría y Administración*, 62(4), pp.1393-1407. <https://doi.org/10.1016/j.cya.2017.06.015>.
- Radhakrishna, V., Ravi, H., Elango, S., Divyashree, V., Jaganathan, A. and Ponnusamy, M., 2024. Future of knowledge management in investment banking: Role of personal intelligent assistants. *Methodological Innovations*, 17(4), pp.229-247. <https://doi.org/10.1177/20597991241287118>.
- Rahman, M., Ming, T.H., Baigh, T.A. and Sarker, M., 2023. Adoption of artificial intelligence in banking services: an empirical analysis. *International Journal of Emerging Markets*, 18(10), pp.4270-4300. <https://doi.org/10.1108/IJOEM-06-2020-0724>.
- Reputation Institute., 2020. *Global RepTrak 100: The World's Most Reputable Companies*. Reputation Institute.
- Ross, SA., Westerfield RW. and Jaffe J., 2019. *Corporate Finance*. 12th Edition. McGraw-Hill Education.
- Sadok, H., Sakka, F. and El Maknoui, M.E.H., 2022. Artificial intelligence and bank credit analysis: A review. *Cogent Economics & Finance*, 10(1), p.2023262. <https://doi.org/10.1080/23322039.2021.2023262>.
- Saunders, A. and Allen, L., 2010. *Credit risk management in and out of the financial crisis: new approaches to value at risk and other paradigms*. John Wiley & Sons. <https://doi.org/10.1002/9781118267981>.
- Stavropoulou, E., Spinthiropoulos, K., Garefalakis, A., Ragazou, K. and Gonidakis, F., 2023. The role of social banking in the success and sustainable business continuity of SSMEs. *International Journal of Financial Studies*, 11(3), p.86. <https://doi.org/10.3390/ijfs11030086>.
- Sterman, J.D., 2000. *Business Dynamics: Systems thinking and modeling for a complex world*. MacGraw-Hill Company.
- Su, X. and Wang, Y., 2025. Factor conditions and capability building of artificial intelligence empowered digital transformation in the banking sector: a case study of a Chinese bank. *International Journal of Technology Management*, 97(2-3), pp.162-194. <https://doi.org/10.1504/IJTM.2025.143587>.
- Terko, A., Žunić, E., Donko, D. and Dželihodžić, A., 2019, October. Credit scoring model implementation in a microfinance context. In *2019 XXVII International Conference on Information, Communication and Automation Technologies (ICAT)* (pp. 1-6). IEEE. <http://dx.doi.org/10.1109/ICAT47117.2019.8939036>.
- Thongsri, N. and Tripak, O., 2024. Does social banking matter in times of crisis? Evidence from the COVID-19 pandemic: a combined SEM-neural network approach. *International Journal of Social Economics*, 51(2), pp.227-247. <https://doi.org/10.1108/IJSE-10-2022-0709>.
- Venanzi, D. and Matteucci, P., 2022. The largest cooperative banks in Continental Europe: a sustainable model of banking. *International Journal of Sustainable Development & World Ecology*, 29(1), pp.84-97. <https://doi.org/10.1080/13504509.2021.1919784>.
- Zamany, A., Khamseh, A. and Iranbanfard, S., 2024. Unveiling the Landscape of High-Tech Transfer in Industry 5.0: A Text Mining Exploration. *Journal of AI and Data Mining*, 12(3), pp.369-392. <https://doi.org/10.22044/jadm.2024.14580.2558>.

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- Eberlein RL. 1984. Simplifying dynamic models by retaining selected behavior modes. PhD Thesis, Massachusetts Institute of Technology, Cambridge, MA.
- Forrester, JW. 1991. Longer-term economic changes. D-4207-1, MIT System Dynamics Group Literature Collection. Available from the System Dynamics Society: <https://www.systemdynamics.org/mit-sdgroup-literature-collection>.
- Graham AK. 1980. Parameter estimation in system dynamics modeling. In Randers J. (ed.) *Elements of the System Dynamics Method*. Productivity Press, Cambridge MA, 143-161.
- Homer JB. 1983. Partial-model testing as a validation tool for system dynamics. In *Proceedings of the 1983 International System Dynamics Conference*. Chestnut Hill, MA, System Dynamics Society.
- Naumov S, Oliva R. 2018. Structural Dominance Analysis Toolset. Retrieved September 17, 2019, from <http://people.tamu.edu/~roliva/research/sd/sda/>.
- Sterman JD. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Irwin/McGraw-Hill, Boston.
- Tan B, Anderson EG, Dyer JS, Parker GG. 2010. Evaluating system dynamics models of risky projects using decision trees: Alternative energy projects as an illustrative example. *System Dynamics Review* 26(1): 1-17.

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Instructions before submission

Short checklist

Please make sure all the following files have been prepared before submission:

1. Assignment of Copyright Form
2. Conflict of interest declaration and author agreement Form
3. Title page: MS Word template of Title page based on Guide for Authors
4. Main manuscript: MS Word template of Main manuscript based on Guide for Authors
5. Supplementary files (if applicable)
6. Contact information for all authors (including First and last names, name of institutions with complete addresses, university or organizational e-mail addresses, ORCID IDs for authors, the corresponding author's full affiliation and phone number)
7. Key words
8. References in Harvard style