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# Redesigning the Wheat and Flour Supply Chain Network Under Uncertainty: A Case Study of Iran

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**Abstract**

Supply Chains (SC) are increasingly affected by internal and external factors such as floods, earthquakes, war, and sanctions, creating significant uncertainty. The wheat and flour SC directly impacts household diets, and any disruption can lead to severe social, political, and economic consequences. This study presents a Mixed-Integer Linear Programming (MILP) model to minimize total costs. The model addresses a multi-product, multi-period problem that includes seven levels: farms, import points, silos (if construction), flour production plants, warehouses, and both essential and non-essential customers. To account for uncertainty, a two-stage stochastic programming approach is applied. In the first stage, the model identifies the optimal locations for silo construction. In the second stage, it optimizes the flow of goods across the network based on different scenarios. The results show the ideal locations for silo construction, the required import volume for each scenario, and flour shortages for non-essential customers, ultimately helping reduce dependency on imports for essential goods.

**Keywords:** Supply chain network redesign, Wheat and flour integrated network design, Wheat import planning, Two-stage stochastic programming, Location and allocation.

## 1 | Introduction

Wheat and flour are central to the global food system, serving a crucial dietary function worldwide. The Supply Chain (SC) for these commodities is characterized by its fragility and complexity, influenced by a combination of intrinsic and extrinsic factors. Bread, a staple food for millions globally, represents the primary output of this SC. The consistent availability of a resource is paramount for global food security. Any disruption or shortage in its supply can precipitate widespread repercussions, impacting not only economic stability but also social and political equilibrium. The significance of the wheat and flour SC is paramount;

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even minor disruptions within it can precipitate considerable ramifications for both populations and governmental stability. Therefore, meticulous attention to the inherent challenges confronting this SC is imperative to safeguard a consistent food supply and avert severe socio-economic repercussions.

The crucial role of wheat and its derivatives as a national dietary food highlights the necessity for strategic planning for its Supply Chain Management (SCM) and provision. A foundational step toward refining management practices and facilitating informed decision-making, thereby boosting efficiency and productivity, involves comprehending the prevailing trends within this sector. In contemporary times, the nation's wheat requirements are fulfilled by combining internal cultivation and foreign procurement. Part of the domestically produced wheat is utilized by agriculturalists for rural bread production, seed purposes, and livestock feeding. The outstanding quantity is procured by the government through established guaranteed price mechanisms. Following its procurement, wheat is transferred to designated storage facilities. Imported wheat, which typically arrives at the nation's ports, is subsequently distributed throughout the provinces [1]. Each year, a significant quantity of grain is moved from purchasing centers and ports to these storage facilities, then to our mills and end-consumption points. The grain SC can be analyzed from both strategic and operational perspectives. Long-term decisions primarily involve selecting suppliers for imported grain [1]. Conversely, mid-term decisions focus on optimizing the quantity of imports, managing the flow of both domestic and imported wheat, developing storage strategies, overseeing the production of wheat-based products, and allocating resources to meet demand effectively [1-2].

Maintaining the stability of this vulnerable SC demands both rigorous monitoring and strategic foresight. A comprehensive understanding of various influencing factors, both internal and external, is crucial. These factors encompass natural disasters, geopolitical instabilities, economic sanctions, and global market price volatility. To enhance the overall resilience of this system, it is essential to incentivize domestic agricultural production of wheat, thereby mitigating reliance on imported grains for this critical commodity. As previously emphasized, these products are integral to food security, yet their import management is frequently underestimated. By fostering domestic production, we can effectively mitigate the risk of shortages and ensure a consistent supply of essential food products.

This research aims to develop a stochastic programming model for redesigning the wheat and flour SC. The primary objectives are to determine the optimal locations for constructing mills and to optimize the network flow. Notably, this study utilizes a two-stage stochastic modeling approach, which is an infrequent application within this specific research context. The main goals of the paper include:

I. Finding the best locations for mill construction to improve efficiency and lower transportation expenses.

II. Catering to two categories of flour customers (essential and non-essential) and wheat customers to satisfy varied market needs;

III. Focusing on the use of domestic wheat for mills while restricting imports to certain conditions to decrease reliance on foreign sources and bolster local production.

IV. Implementing the model in a real-world case study in Iran to evaluate its effectiveness in actual market scenarios.

V. Employing scenario-based stochastic programming, backed by historical data on wheat farming and current demand, to deliver the best solutions and mitigate risks;

VI. Reducing expected costs and enhancing the sustainability of the SC;

VII. Assessing the value of imports and identifying the most efficient import ports to cut expenses and enhance the distribution network's efficiency.

The present study proposes a comprehensive and practical solution to enhance the wheat and flour SC within Iran.

This paper is structured as follows. Section 2 provides a comprehensive overview of the theoretical background of the wheat and flour SC. Section 3 meticulously defines the problem and its underlying assumptions, subsequently presenting the deterministic mathematical model. Following this, a two-stage scenario-based stochastic model for the wheat and flour SC is formulated. Section 4 is dedicated to the analysis and discussion of the model's results. Finally, Section 5 offers managerial recommendations, presents conclusions, and suggests avenues for future research.

# 2 | Literature Review

Research concerning wheat SC and its derivative products remains limited. To comprehensively address existing knowledge gaps, prior research studies have been categorized into three principal domains: 1) Agricultural food SCs (AFSCs), 2) uncertainty in SCs, and 3) wheat and flour SCM. Each section will provide an in-depth examination of its respective topic, offering insights into the current research landscape and identifying avenues for future investigation.

## 2.1 | Agriculture Food Supply Chain (AFSCs)

A significant body of research has concentrated on the design and redesign of AFSC structures, primarily to enhance their efficiency and sustainability. For instance, Thakur et al. [3] developed a multi-objective Mixed-Integer Programming (MIP) model to improve traceability within grain SCs, thereby minimizing food safety risks linked to the aggregation of different product lots. Their proposed model effectively optimized lot aggregation levels and blending costs, ensuring traceability and cost efficiency in grain handling operations. Moreover, Asgari et al. [4] investigated a practical, logistical challenge by employing integer programming to determine optimal inter-provincial wheat transportation volumes throughout the year, thereby offering an efficient solution for wheat SCM. In contrast, Craige et al. [5] highlighted the necessity of a comprehensive approach to biomass SC modeling, integrating key factors, such as site selection, harvesting, transportation, and processing costs, to evaluate the economic feasibility of various production methodologies.

Within the domain of AFSC distribution, Ghezavati et al. [6] developed a periodic planning model specifically designed to distribute fresh produce. This model, exemplified through a tomato SC case study, aimed to boost distributor profits. A key feature of their approach was optimizing logistical decisions by incorporating qualitative segregation of the produce. Cárdenas-Barrón et al. [7] developed a heuristic approach to address the selective and periodic inventory routing problem for collecting waste vegetable oil. Their method leveraged the Return On Assets (ROA) method to identify near-optimal solutions efficiently. This study proposes a comprehensive framework for supplier selection within the processed food industry, explicitly accounting for the impact of uncertainty. This approach integrates tactical production and distribution planning to maximize profits while simultaneously minimizing risks that could jeopardize service levels. This methodology underscores the inherent complexities of food SCM [8].

Further studies have explored specific SC challenges across diverse contexts. For instance, Mogale et al. [9] developed a Mixed-Integer Non-Linear Programming (MINLP) model to optimize transportation within India's Public Distribution System (PDS). This model aimed to efficiently move surplus grains to states experiencing deficits while also accounting for crucial factors, such as silo storage, vehicle preferences, seasonal procurement, and storage capacity. Gholamian et al. [1] developed an integrated model for the wheat SC, optimizing both long-term decisions (such as supplier selection and silo locations) and mid-term decisions (such as wheat distribution and blending). Building on this, Hosseini-Motlagh et al. [2] introduced a novel model for redesigning a sustainable wheat SC. This model uniquely incorporates uncertainty while optimizing critical elements, including suppliers, silos, flour factories, and demand zones, to boost total network performance.

## 2.2 | Uncertainty in Supply Chain

Uncertainty is an inherent feature of SCs, and its influence on AFSCs is particularly pronounced due to the unpredictable character of environmental, market, and demand variables.

To improve the understanding and management of uncertainty, Yazdani et al. [10] developed an enhanced approach to the fuzzy Multi-Criteria Decision-Making (MCDM) method. This involved integrating interval fuzzy values into the Decision-Making Trial And Evaluation Laboratory (DEMATEL) method, which was subsequently embedded within the Quality Function Deployment (QFD) framework. In addition, Jarernsuk et al. [11] developed mathematical programming models to optimize SCs for perishable goods. Their approach, which utilized possibilistic linear programming, aimed to enhance flexibility in managing fluctuations in unit prices and costs, thereby mitigating uncertainty within the SC. Their research underscores the intricate nature of uncertainty and its direct influence on decision-making processes within AFSCs.

Certain studies have concentrated on strategic and tactical decision-making aimed at optimizing the performance of AFSCs. For instance, Meena et al. [12] introduced a model incorporating both internal capabilities and deficiencies alongside external opportunities and risks, thereby offering a strategic viewpoint toward AFSCs. This model employed the Analytical Hierarchy Process (AHP) and fuzzy-AHP methods to analyze and prioritize these factors effectively. In a separate study, Cruz et al. [13] introduced a Mixed-Integer Linear Programming (MILP) model designed specifically for the AFSC. Their research focused on capacity planning, technology selection, and product flow optimization to boost the Expected Net Present Value (ENPV). Govindan et al. [14] reviewed diverse planning decisions and network structures within SCM. Their work specifically explored various optimization approaches employed to address uncertainty in SC networks. These techniques encompass recourse-based stochastic programming, risk-averse stochastic programming, robust optimization, and fuzzy mathematical programming. Additionally, Motevalli-Taher et al. [15] investigated AFSC sustainability by incorporating uncertainty in wheat demand and employing simulation to eliminate this challenge. Altogether, these studies provide significant insights into the theoretical and practical methodologies for managing uncertainty within AFSCs.

## 2.3 | Wheat and Flour Supply Chain

Wheat and its derivatives are currently recognized as a fundamental global food source. In a relevant case study, Hosseini Motlagh et al. [16] investigated Iran's wheat SC and its associated organizations. Their research introduced a novel mathematical model aimed at optimizing the total cost of designing the wheat SC network. This model effectively integrated the wheat SC's collection, production, inventory, and distribution phases. Furthermore, Asgari et al. [4] developed an optimization model for the monthly transportation of wheat from storage facilities to consumers, employing a combination of ILP and a genetic algorithm.

Gholamian et al. [1] developed an integrated wheat SC model incorporating various decision-making levels. This included technical decisions (such as supplier selection), strategic decisions (such as determining optimal silo locations), and mid-term decisions (such as wheat allocation and distribution). Their comprehensive model specifically addressed supplier selection, import quantity determination, wheat distribution, and the production of wheat-based products. Separately, Alberts et al. [17] investigated transportation disruptions during product movement from factories to the subsequent SC level (i.e., distribution centers). Their research focused on evaluating the efficacy of different strategies for mitigating transportation-related issues.

Flour, being the main derivative of wheat and a critical component in bread manufacturing, is of considerable importance within both the food and industrial sectors. In response, Gholamian et al. [1], [18] developed an optimization model specifically for designing the flour SC network, particularly centered on strategic import decisions and mid-level allocation strategies. Motevalli-Taher et al. [15] developed a sustainable mathematical model for the bread SC. Their model simultaneously aimed to reduce economic factors, such as network costs, and environmental concerns, such as water consumption. Concurrently, it sought to boost job opportunities, thereby addressing a significant social dimension within the bread SC. Moreover, Djuric et al. [19] explored inflation control strategies in Serbia, specifically focusing on the impact of export restrictions and domestic consumption regulations for wheat and bread. Their research employed a Markov model to analyze the associated profit margins.

Trisna et al. [20] addressed the complexities of flour transportation by developing a comprehensive model for wheat and flour SC. Their research uniquely incorporated the concept of raw material substitution. The model specifically considered both supplier capacity and product demand under conditions of uncertainty. To formulate this intricate problem, they employed fuzzy integer non-linear programming and subsequently utilized a genetic algorithm to derive the best solution.

The distribution and production of bread, as a fundamental food, have also been a focus of academic inquiry. In this area, Kowalczyk et al. [21] conducted a comparative analysis of traditional and industrial methods for wheat harvesting and bread production. Their research culminated in developing a mathematical model for the wheat SC, encompassing all stages from wheat cultivation to the delivery of the final product. The model sought to optimize wheat production, imports, and water consumption while simultaneously reducing SC costs. Additionally, it incorporates decisions related to transportation, inventory, and silo establishment. In a related study, Zakaei et al. [22] introduced a foundational approach for strategic positioning and tactical allocation within a four-tier SC. They applied it to a real-world problem to boost a bread SC network. Concurrently, Dibani et al. [23] investigated the influence of consumer preferences and bread characteristics on demand.

The wheat and flour SC is fundamental to a nation's social and political stability, directly influencing citizens' daily diets. Consequently, maintaining a stable SC is paramount, particularly amidst prevailing uncertainties. To thoroughly grasp the existing complexities and challenges within this domain, we undertook a comprehensive review of prior research, the findings of which are summarized in *Table 1*. While a significant body of research addresses AFSCs, there is a notable scarcity of studies that incorporate uncertainty into their model formulations and optimizations. The majority of these investigations primarily deal with the broader SC dynamics, with limited exploration of silo construction and allocation decisions under uncertain conditions. This gap highlights a critical need for more sophisticated modeling approaches that merge both uncertainty and long-term infrastructure planning into tactical decision-making for the design of more robust SC.

**Table 1. Review of the related studies.**

| Authors | Year | Model | Period | | Products | | Facility Level | Uncertainty | Case Study | Solution Method |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Single | Multi | Single | Multi | | | | |
| Asgari et al. [4] | 2013 | MILP | ✓ | - | ✓ | - | Farm, Warehouse, Factory | - | Wheat, Iran | Metaheuristic |
| Djuric et al. [21] | 2016 | - | ✓ | - | ✓ | - | Grain market, Export | - | Wheat and bread, Serbia | Markov-switching |
| Gholamian et al .[1] | 2017 | MILP | - | ✓ | - | ✓ | Farm, Import, Silo, Factory, Market | - | Wheat, Iran | Mathematics |
| Tanksale and Jha [26] | 2017 | MINLP | - | ✓ | ✓ | - | Farm, Silo, Warehouse | - | Grain, Indian | Metaheuristic |
| Chavez et al. [27] | 2018 | MILP | - | ✓ | ✓ | - | Supplier, Gathering centers, Blending | - | Coffee crop residue, Colombia | e-constraint |
| Essiena et al. [28] | 2018 | MILP | ✓ | - | ✓ | - | Farm, Export, Market | - | Grain, Ghana | Decision support system |
| Hosseini–Motlagh et al. [17] | 2019 | MILP | - | ✓ | - | ✓ | Supplier, Silo, Factory, Market | Robust | Wheat, Iran | Mathematics |
| Naderi et al. [29] | 2019 | MILP | ✓ | - | ✓ | - | Farm, Silo, Factory | - | Wheat, Iran | Benders decomposition |
| Motevalli-Taher et al. [16] | 2020 | MILP | - | ✓ | - | ✓ | Farms, Import points, Silos, Factories, Customers, market | Simulation | Wheat, Iran | Meta-goal programming |
| Hosseini–Motlagh et al. [2] | 2020 | MILP | - | ✓ | - | ✓ | Supplier, Silo, Factory, Market | hybrid stochastic fuzzy-robust | Wheat, Iran | Goal Programming |
| Navazi et al. [30] | 2021 | MINLP | - | ✓ | ✓ | - | Supplier, Distributor, Retailer, Recycle | Fuzzy | Bread, Iran | Metaheuristic |
| Babazadeh et al. [31] | 2021 | LP | - | ✓ | ✓ | - | Farm, Import, Silo, Customer | Fuzzy | Wheat, Iran | Epsilon Constraint/ Lexicographic |
| Seydanlou et al. [32] | 2022 | MILP | - | ✓ | ✓ | - | Farm, Distributor, Factory, Market, Recycling center | | Olive, Iran | Epsilon-constraint/ Metaheuristic |
| Olfati et al. [33] | 2023 | MILP | - | ✓ | ✓ | - | Farm, Collecting center, Processing z, packaging center, Market | Robust optimization | Tea, Iran | Goal programming |
| Yousefi-Babadi et al. [34] | 2023 | MILP | ✓ | - | ✓ | - | Supplier, Factory, Customer | Robust | Wheat and flour, Iran | Lagrangian relaxation |
| Rahbari et al. [35] | 2024 | MILP | ✓ | - | ✓ | - | Farm, Import, Customer | Robust | Wheat, Iran | Mathematics |
| Sharifi et al. [36] | 2024 | MILP | - | ✓ | ✓ | - | Farm, Distributor, Factory, Internal customer, Foreign customer | Fuzzy | Wheat, Canada | Mathematics |
| This study | 2025 | MILP | - | ✓ | - | ✓ | Farm, Import, Silo (Construction), Factory, Warehouse, Essential customer, Non-Essential customer | Two-Stage Scenario-based stochastic programming | Wheat and flour, Iran | Mathematics modeling |

# 3 | Problem Definition

The wheat and flour SC is fundamental to both food security and economic stability. The model proposed in this research aims to optimize this critical SC by effectively managing its central components, encompassing farms, import points, silos, flour mills, warehouses, and various customer types. A core objective of the model is to identify the optimal locations for new silo construction strategically. Wheat, sourced from either domestic cultivation or international imports, undergoes initial transportation to silos for storage. Following storage, it is distributed to key consumers, including the agricultural sector and animal feed producers. Subsequently, the wheat is transferred to flour mills for processing into flour, which is then held in warehouses. Essential flour consumers, such as bakeries producing staple food products, receive priority in allocation. Any surplus flour is then directed to non-essential consumers, including confectionery manufacturers. A visual representation of this problem overview is provided in *Fig. 1*.

This model extends beyond merely managing storage and distribution; it comprehensively optimizes the transportation of wheat from its points of origin, including farms and import locations, to silos and subsequently to flour mills situated across various regions. Since flour is a staple food, mills and warehouses are geographically dispersed nationwide. The model ensures that these facilities operate at maximum efficiency to meet demand. Furthermore, it assesses the necessity of constructing new silos to enhance overall storage capacity.

## 3.1 | Assumptions

I. The proposed model operates over 9 years and involves multiple periods and products.

II. The construction of silos is scheduled for the first two years of these 9 years.

III. The initial network is designed without silos, and the model identifies the best locations for silos at the outset.

IV. It is assumed that all silos will be of medium size and will fulfill the minimum storage requirements.

V. The model permits the establishment of up to two silos in each potential province.

VI. Shortages of flour for essential customers are not allowed, while shortages for non-essential customers are acceptable.

VII. The initial inventory level in warehouses is set to zero.

VIII. All domestically produced wheat must be utilized prior to any imported wheat being permitted.

IX. The supply priority within the network is arranged as follows: Wheat first, then essential flour, followed by non-essential flour.

X. All facilities, including silos, mills, and warehouses, are situated in the provincial capitals.

XI. Uncertainty factors involve import costs and crop loss rates at the farm level.

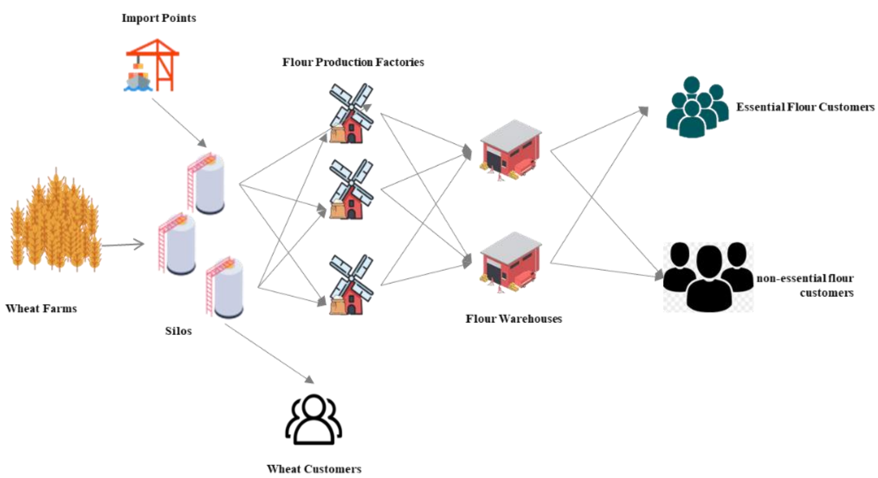


**Fig. 1. Overview of the problem.**

## 3.2 | Notation and Model Formulation

**Indicates**

| | |
|---|---|
| I | The set of farms, $i \in I$. |
| J | The set of siloes, $j \in J$. |
| K | The set of mills, $k \in K$. |
| L | The set of flour warehouses, $l \in L$. |
| P | The set of import ports, $p \in P$. |
| A | The set of essential flour customers, $a \in A$. |
| B | The set of non-essential flour customers, $b \in B$. |
| W | The set of wheat customers, $w \in W$. |
| T | The set of periods, $t \in T$. |
| S | The set of scenarios, $s \in S$. |

**Parameters**

| | |
|---|---|
| $f_{it}$ | Management and operational cost of cultivation in farm i on period t. |
| $f_{jt}$ | The cost of construction of silo j on period t. |
| $f_{kt}$ | Management and operational cost of mill k on period t. |
| $f_{lt}$ | Management and operational cost of warehouse l on period t. |
| $C_{ijt}$ | Transportation cost from supplier i to silo j on period t. |
| $C_{jkt}$ | Transportation cost from silo j to mill k on period t. |
| $C_{klt}$ | Transportation cost from mill k to warehouse l on period t. |
| $C_{lat}$ | Transportation cost from warehouse l to essential flour customer a on period t. |
| $C_{lbt}$ | Transportation cost from supplier i to non-essential flour customer b on period t. |
| $C_{jwt}$ | Transportation cost from silo j to wheat customer w on period t. |
| $C_{pjt}$ | Transportation cost from import port p to silo j on period t. |
| $Cap_j$ | Capacity of silo j. |
| $Cap_k$ | Capacity of mill k. |
| $Cap_l$ | Capacity of warehouse l. |
| $D_{wt}$ | The demand for wheat by customer w on period t. |
| $D_{at}$ | The demand for flour by essential flour customer a on period t. |
| $D_{bt}$ | Demand for flour by non-essential flour customers during period t. |
| $\Omega_{kt}$ | The cost of converting wheat into flour at mill k on period t. |
| $Pi_{it}$ | Cultivated area of farm i on period t. |
| $Pi_{pt}$ | Approved import capacity of wheat from import port p on period t. |
| $\alpha_{is}$ | Wheat loss rate in the field. |
| rr | Conversion rate of wheat to flour in the mill. |
| cc | Shortage cost for essential flour and wheat. |
| cb | Shortage cost for non-essential flour. |
| SS | The safety stock. |
| $Im_s$ | Cost of importing wheat. |
| $Pa_s$ | The probability of scenario accuracy. |

**Variables**

| | |
|---|---|
| $X^1_{ijts}$ | The amount of wheat shipped from farm i to silo j on period t. |
| $X^2_{jkts}$ | The amount of wheat shipped from silo j to mill k on period t. |
| $X^3_{klts}$ | The amount of flour shipped from mill k to warehouse l on period t. |
| $X^4_{lats}$ | The amount of flour shipped from warehouse l to essential flour customer a on period t. |
| $X^5_{lbts}$ | The amount of flour shipped from warehouse l to non-essential flour customer b on period t. |
| $X^6_{jwts}$ | The amount of wheat shipped from silo j to wheat customer w on period t. |
| $X^7_{pjts}$ | The amount of wheat shipped from import port p to silo j on period t. |
| $L^1_{ats}$ | The amount of shortage of flour for essential flour customer a on period t. |
| $L^2_{bts}$ | The amount of shortage of flour for non-essential flour customers during period t. |
| $L^3_{wts}$ | The amount of shortage of wheat for wheat customer w on period t. |

| | |
|---|---|
| $y^1_{jt}$ | Equal to 1 if the silo is chosen to be built in province j, 0 otherwise. |
| $y^2_{kts}$ | Equal to 1 if the mill is chosen to be open in province k, 0 otherwise. |
| $y^3_{pts}$ | Equal to 1 if importing wheat is allowed from port p, 0 otherwise. |

# 4 | Mathematical Model

Safaei et al. [37] previously addressed this problem using a deterministic model. Building upon that work, the current study introduces a stochastic model to address the same problem.

Uncertainty in SC and logistics network design can be categorized into two primary categories: "Operational parameter uncertainty" and "network disruption uncertainty."

Operational parameter uncertainty: This type refers to the typical fluctuations inherent in business processes, such as unpredictable shifts in demand or variations in the raw materials supply. These factors can significantly challenge SCM [38].

Network disruption uncertainty: This type encompasses infrequent events characterized by a low likelihood of occurrence but possessing substantial consequences for network performance. These disruptions can originate from natural disasters, such as floods and earthquakes, or human-induced factors, including wars and terrorist attacks. Such occurrences have the potential to impede the SC severely, thereby underscoring the critical need for strategic planning to bolster network resilience [38].

In contrast to numerous SCs where demand uncertainty significantly impacts operations, specialists in this domain contend that demand volatility is not a primary concern for this particular study. Given that wheat and flour are staple commodities, their consumption is directly correlated with per capita consumption, which is mainly dependent on population size. Consequently, the demand for these products remains relatively stable and is therefore not treated as an uncertain parameter within this model.

Instead, two principal sources of uncertainty considerably influence this SC:

I. Wheat loss rate in the field, which is affected by climatic conditions (such as flood, earthquake, and famine) and internal variables, culminating in fluctuations in domestic wheat production.

II. Import prices, which are influenced by global events (such as wars, climate conditions, economic sanctions, and geopolitical tensions), are a substantial uncertainty variable in the model.

Considering the various sources of uncertainty inherent in the system, this study adopts a two-stage stochastic programming approach. In the first stage, the model specifies the optimal locations for silos. Subsequently, the second stage focuses on optimizing flow allocation decisions across the SC under various scenarios.

The objective function in this model aims to minimize the expected total cost, encompassing both operational expenses and initial capital investments across several uncertainty scenarios. The set S denotes the generated scenarios that capture the uncertainty in yield rates and import costs. *Table 2* outlines the six probable scenarios taken into account in this study.

$$\begin{aligned}\text{Min } Z_1 = & \sum_i \sum_t f_{it}\, Pi_{it} + \sum_j \sum_t f_{jt}\, y^1_{jt} + \sum_k \sum_t \sum_s Pa_s\, f_{kt}\, y^2_{kts} + \sum_l \sum_t f_{lt} \\ & + \sum_i \sum_j \sum_t \sum_s Pa_s\, C_{ijt}\, X^1_{ijts} + \sum_j \sum_k \sum_t \sum_s Pa_s\, C_{jkt}\, X^2_{jkts} \\ & + \sum_k \sum_l \sum_t \sum_s Pa_s\, C_{klt}\, X^3_{klts} + \sum_k \sum_l \sum_t \sum_s Pa_s\, X^3_{klts}\, \Omega_{kt} \\ & + \sum_l \sum_a \sum_t \sum_s Pa_s\, C_{lat}\, X^4_{lats} + \sum_l \sum_b \sum_t \sum_s Pa_s\, C_{lbt}\, X^5_{lbts} \\ & + \sum_j \sum_w \sum_t \sum_s Pa_s\, C_{jwt}\, X^6_{jwts} + \left( \sum_p \sum_j \sum_t C_{pjt} + Im_s \right) \sum_p \sum_j \sum_t Pa_s X^7_{pjts} \\ & + CC \left( \sum_a \sum_t \sum_s Pa_s\, L^1_{ats} + \sum_w \sum_t \sum_s Pa_s\, L^3_{wts} \right) + cb \sum_b \sum_t \sum_s Pa_s\, L^2_{bts} \end{aligned} \quad (1)$$

The objective function, as formalized in *Eq. (1)*, is designed to reduce anticipated total costs. These costs encompass both fixed and variable expenditures, such as management expenses per hectare of cultivated land, construction costs for new silos, operational and production costs for active flour mills, warehouse management costs, transportation costs across all network levels, import costs, and shortage costs.

$$Pi_{it}(1-\alpha_{is}) \geq \sum_j X^1_{ijts}, \text{ for all } i, t, \quad (2)$$

$$y^3_{pts} Pi_{pt} \geq \textstyle\sum_j X^7_{pjts}, \text{ for all } p, t, s \quad (3)$$

$$\textstyle\sum_i X^1_{ijts} + \sum_p X^7_{pjts} \geq \sum_w X^6_{jwts} + \sum_k X^2_{jkts}, \text{ for all } j, t, s, \quad (4)$$

$$\textstyle\sum_k X^3_{klts} \geq \sum_a X^4_{lats} + \sum_b X^5_{lbts}, \text{ for all } l, t, s, \quad (5)$$

$$rr \textstyle\sum_j X^2_{jkts} \geq \sum_l X^3_{klts}, \text{ for all } k, t, s, \quad (6)$$

$$\textstyle\sum_l X^4_{lats} = D_{at} - L^1_{ats}, \text{ for all } a, t, s, \quad (7)$$

$$\sum_l X^5_{lbts} \leq D_{bt} - L^2_{bts}, \text{ for all } b, t, s, \quad (8)$$

$$\textstyle\sum_j X^6_{jwts} = D_{wt} - L^3_{wts}, \text{ for all } w, t, s, \quad (9)$$

$$\textstyle\sum_w X^6_{jwts} + \sum_k X^2_{jkts} \leq Cap_j * \sum_{t=1}^{T} y^1_{jt}, \quad \text{for all } j, t, s, \quad (10)$$

$$rr \textstyle\sum_j X^2_{jkts} \leq Cap_k, \quad \text{for all } k, t, s, \quad (11)$$

$$\textstyle\sum_l X^3_{klts} \leq Cap_l, \quad \text{for all } l, t, s, \quad (12)$$

$$\textstyle\sum_w X^6_{jwt} + \sum_k X^2_{jkt} \geq SS * \sum_{t=1}^{T} y^1_{jt}, \quad \text{for all } j, t, \quad (13)$$

$$\textstyle\sum_t y^1_{jt} \leq 2, \text{ for all } j, \quad (14)$$

$$\textstyle\sum_j y^1_{jt} = k, \text{ for all } t = 1, \quad (15)$$

$$\textstyle\sum_{T-t1}^{T} y^1_{jt} = 0, \quad \text{for all } t, \quad (16)$$

$$\textstyle\sum_s Pa_s = 1, \quad (17)$$

$$y^1_{jt}, y^2_{kts}, y^3_{pts} \in \{0,1\}, \quad \text{for all } i, k, p, t, \quad (18)$$

$$X^1_{ijts}, X^2_{jkts}, X^3_{klts}, X^4_{lats}, X^5_{lbts}, X^6_{jwts}, X^7_{pjts}, L^1_{ats}, L^2_{bts}, L^3_{wts} \geq 0, \quad \text{for all } i, j, k, l, a, b, w, t, s. \quad (19)$$

The constraints within this mathematical model are formulated to augment the expected value of the wheat and flour SC across various scenarios. These constraints specifically address critical aspects of production, storage, transportation, and processing. Their inclusion ensures the efficient flow of wheat and flour while simultaneously sustaining SC balance and operational feasibility. *Eq. (2)* represents the farm output constraint for each scenario, which incorporates varying loss rates. This constraint stipulates that the volume of wheat supplied from each farm must be equivalent to the quantity of healthy wheat harvested from the agricultural land. Furthermore, the import constraint *Eq. (3)* ensures that the total volume of imported wheat does not surpass the annual import quota established by regulatory bodies. This phenomenon occurs when permitted within various scenarios. To maintain consistency in the quantity of goods entering and exiting each SC level, several flow balance constraints are incorporated. *Eq. (4)* ensures that the wheat dispatched from silos does not surpass the available stock. Similarly, *Eq. (5)* imposes a comparable constraint on flour, mandating that the outflow from storage cannot exceed the existing inventory level. Constraint regarding the wheat-to-flour conversion *Eq. (6)* establishes the connection between the quantity of processed wheat and the resulting flour produced, according to the conversion rate.

To satisfy customer needs, the supply of essential flour and non-essential flour and wheat, respectively, is governed by demand fulfillment constraints, *Eqs. (7)-(9)*. Due to the restricted capacity of each SC facility, *Eq. (10)* guarantees that the total amount of wheat stored in a silo does not surpass its storage limit, provided that the silo was built in the current or prior periods. Moreover, *Eq. (11)* guarantees that the quantity of wheat processed in flour mills remains within their production capacity. Concurrently, *Eq. (12)* restricts the volume of flour stored in warehouses to their maximum capacities. To bolster SC resilience, a minimum inventory constraint *Eq. (13)* mandates that newly built silos sustain a safety stock equivalent to two months' average consumption rate. Furthermore, the restriction on silo construction, *Eq. (14),* guarantees an even allocation of storage facilities throughout the provinces, adhering to government regulations. The initial condition constraint *Eq. (15)* specifies the number of silos present at the start of the first period. At the same time, *Eq. (16)* prohibits the construction of silos in the later stages of the planning timeline. The total probabilities for scenarios must not exceed one, and *Eq. (17)* regulates this. Ultimately, the nature of the decision variables is precisely defined by variable constraints *Eq. (18)* and *Eq. (19)*. *Eq. (18)* designates binary variables (0 or 1), specifying whether a silo is constructed, a flour mill is operational, or wheat imports are allowed. *Eq. (19)* specifically mandates that all other variables, including quantities of wheat and flour, maintain continuous and non-negative values. Collectively, these constraints are designed to guarantee the efficient wheat and flour SCM, thereby achieving particular objectives, such as cost minimization, enhanced operational efficiency, and the secure and consistent supply of these crucial products.

**Table 2. Adopted scenarios.**

| Scenario Number | Scenario Definition | $Pa_s$ |
|---|---|---|
| Scenario 1 | High wheat loss rate in the field, high import prices | 0.09 |
| Scenario 2 | High wheat loss rate in the field, typical import prices | 0.21 |
| Scenario 3 | Typical wheat loss rate in the field, high import prices | 0.15 |
| Scenario 4 | Typical wheat loss rate in the field, typical import prices | 0.35 |
| Scenario 5 | Low wheat loss rate in the field, high import prices | 0.06 |
| Scenario 6 | Low wheat loss rate in the field, typical import prices | 0.14 |

## 4.1 | Data Analysis and Research Findings

This study examines wheat cultivation across 31 provinces and imports through six key ports (Amirabad, Noshahr, Anzali, Chabahar, Bandar Abbas, and Imam Khomeini) in the country, covering the period from 2015 to 2023. The evaluation model encompasses the supply of essential and semi-essential flour and wheat. For computational analysis, this model was coded and solved utilizing the General Algebraic Modeling System (GAMS) optimization software. All experiments were executed on a system with 8 GB of RAM and an Intel Core i7-7500U processor.

Given the unavailability of precise data, this study provided approximate yet realistic cost comparisons for each section. Over nine years, the total projected cost, encompassing wheat imports, domestic cultivation, flour production, multi-stage transportation, and silo construction, is estimated to be approximately 94.681 billion USD. The detailed expenditures for each analyzed scenario are presented in *Table 3*.

**Table 3. Results for scenario-based model.**

| Scenario Number | Operational Costs (Billion USD) | $Pa_s$ |
|---|---|---|
| Scenario 1 | 58.279 | 0.09 |
| Scenario 2 | 58.228 | 0.21 |
| Scenario 3 | 55.630 | 0.15 |
| Scenario 4 | 55.041 | 0.35 |
| Scenario 5 | 53.342 | 0.06 |
| Scenario 6 | 53.333 | 0.14 |
| Total | 55.749 | |

Given wheat's pivotal role in the diet of the Iranian population, the model initially prioritized silo construction in all provinces within the first year. By the second year, as illustrated in *Fig. 2*, an additional eight silos were built in various provinces. The rationale underpinning these decisions is detailed in *Table 4*.

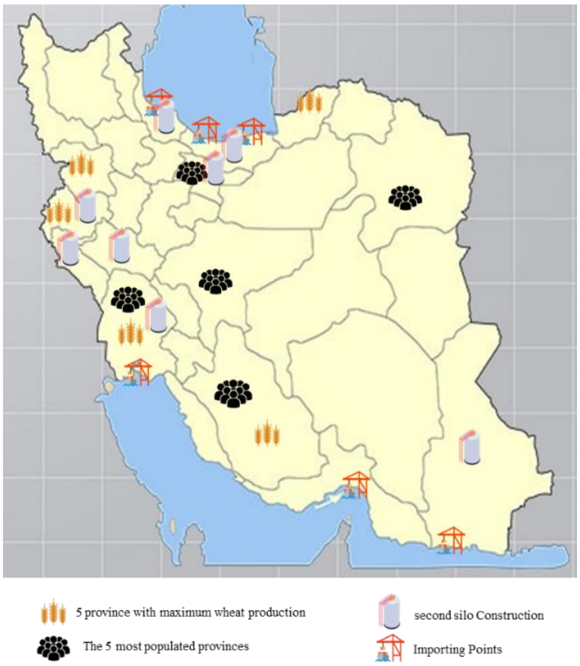


**Fig. 2. The geographical view of province selection for the construction.**

Had the model been configured to supply only non-essential customers, relying solely on safety stock policies and the current factory and warehouse capacities, it would have necessitated the construction of a second silo in 11 provinces. This scenario aligns with the observations made by Safaei et al. [37] in their research. Conversely, if the model aimed to serve essential customers exclusively, a total of 33 silos would suffice for all provinces. As depicted in *Fig. 3*, the model demonstrated a complete reliance on domestic wheat production in Scenarios 1, 3, and 5. Conversely, imports played a pivotal role in the SC within the even-numbered scenarios. In Scenario 2, imports constituted the majority of the supply due to a high rate of wheat loss.

**Table 4. Reasons for selecting provinces for building the second silo.**

| Province | Reasons |
|---|---|
| Ilam | Its proximity to Kerman Shah and Khuzestan province, a major wheat-producing region, and for the latter, it has an importing port and is one of the most populated provinces in the country. |
| Tehran | It is really critical for the capital province. Additionally, it is the most populous province of Iran. |
| Khuzestan | The leading wheat producer in the country includes one import point. |
| Sistanobalochestan | It consists of an importing point. |
| Kerman Shah | One of the largest wheat producers in the country and in the vicinity of Kerman Shah, one of the largest wheat producers. |
| Gilan | It includes an importing point and also the provider of wheat for the north east of the country's flour production. |
| Lorestan | Its proximity to Kermanshah and Khuzestan—both major wheat producers, with Khuzestan also serving as an import point—and to Isfahan, one of the country's most densely populated provinces |
| Mazandaran | It includes two importing point. |

As illustrated in *Table 5*, the ports of Amirabad and Imam Khomeini are identified as the principal entry points for wheat imports into Iran, consistently processing the highest volumes. Conversely, Bandar Abbas and Anzali handle the lowest quantities of imported wheat. Notably, the aggregate volume of wheat imports from Iran's northern and southern regions demonstrates approximate parity.

**Table 5. The import volume varies across different ports.**

| Port | Amir Abad | Imam Khomeini | Chabahar | Noshahr | Anzali | Bandar Abas |
|---|---|---|---|---|---|---|
| Importing volumes | 6456166 | 6151213 | 4100454 | 3932366 | 2358328 | 2235839 |

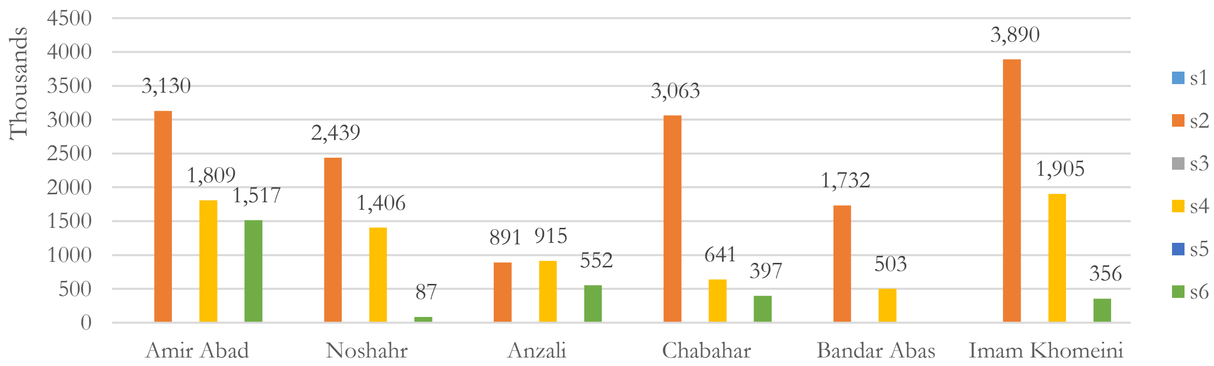


**Fig. 3. To determine the amount of wheat imported in each scenario.**

As expected, the model consistently prevented shortages of essential goods. In the odd-numbered scenarios, the model strategically opted for shortages in non-essential goods, a decision driven by the lower cost of such shortages compared to the combined expenses of importing and distribution. Notably, Scenario 1 exhibited the most significant shortage, primarily attributed to a high rate of wheat loss at the farm level and elevated import prices. Conversely, the volume of wheat imports remained stable across Scenarios 2, 4, and 6. All supporting data for these observations are presented in *Table 6*.

**Table 6. The shortage volume varies across scenarios.**

| Scenario's number | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
|---|---|---|---|---|---|---|
| Shortage volume | 18296520 | 4968136 | 11285960 | 4968136 | 7528171 | 4968136 |

**Table 7. The shortage volume varies per year.**

| Year | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|
| Shortage volume | 12780987 | 2042106 | 4418852 | 5335063 | 3562237 | 4589288 | 6900339 | 4889883 | 7493314 |

# 5 | Conclusion

The present research presents a model designed to optimize the wheat and flour SC network. The model's core function is to determine the optimal quantity of wheat to be imported from various international sources, while simultaneously ensuring the maximal utilization of domestic wheat production. By incentivizing and facilitating increased local wheat cultivation, this model effectively contributes to reducing reliance on imports for this critical grain. The model additionally enhances flour production efficiency and optimizes product distribution across various SC tiers, all while effectively managing uncertainty. The core objective of this model is to satisfy demand at the lowest possible cost, even when confronted with challenging conditions across diverse scenarios. The analysis incorporates multiple variable costs, specifically those associated with wheat cultivation, imports, flour production, transportation, and potential shortages. The model is implemented using GAMS software, thereby precluding the necessity of employing heuristic methods.

This study reveals that about 60% of the total SC costs are attributable to distribution, production, transportation, and shortages. The remaining 40% of the costs are associated with silo construction. From a strategic perspective, 40% of the total costs are linked to long-term decisions, whereas 60% pertain to operational expenses. These cost calculations were performed over nine years, offering a comprehensive understanding of the SC's cost structure.

The second aspect of silo construction and distribution focuses on strategically establishing facilities to supply wheat for flour production across all provinces. This distribution plan is crucial for defining the service area of each silo. Despite the considerable transportation distances for some silos, the model's design strategically identifies which provinces, particularly those equipped with two silos, will serve as primary wheat suppliers, thereby ensuring a stable supply network. Consequently, the model recommends the construction of 39 silos for optimal operational efficiency within the SC.

Regarding import strategies, the model demonstrated a clear divergence based on scenario characteristics. In odd-numbered scenarios, characterized by elevated transportation and import costs, the model opted to forego imports and instead manage shortages for non-essential customers. Conversely, in even-numbered scenarios, the decision to import was directly contingent upon the domestic production level. Analysis reveals that the shortages observed in odd-numbered scenarios significantly exceeded those in even-numbered scenarios. Notably, 2015 exhibited a substantially higher shortage volume compared to other years, primarily attributable to the incomplete construction of silos. In contrast, subsequent years experienced relatively consistent levels of shortages. Amirabad Port, situated in northern Iran, and Imam Khomeini Port, located in the south, are determined as the principal import hubs. Wheat imports constitute less than 15% of the total supply, significantly mitigating reliance on foreign sources. This ratio specifically pertains to essential goods, with a minor proportion allocated to non-essential items. This presents a worthy opportunity for private enterprises to supply non-essential flour to the food industry.

## 5.1 | Managerial Suggestions

In Iran, exceptionally low fuel costs incentivize the selection of longer transportation routes for goods. However, this preference leads to considerable environmental consequences stemming from the extended travel distances. Conversely, elevated global fuel prices diminish the economic viability of exporting goods.

Consequently, it would be more beneficial for managers to meticulously monitor transportation distances and prioritize the optimization of exports to enhance both operational efficiency and environmental sustainability.

Iran's bread consumption significantly exceeds the global average, presenting considerable challenges for food security and resource management. To lessen this reliance, a pragmatic strategy would involve promoting and emphasizing alternative food products. This approach could help diversify national consumption patterns, bolstering food security and fostering more balanced dietary options.

To ensure the stability of the SC, particularly concerning wheat and flour, the establishment of long-term contracts with business partners is strongly advisable. Such agreements would offer enhanced flexibility and facilitate more efficient decision-making during crises, guaranteeing a consistent supply of essential goods and minimizing disruptions within the SC.

### 5.2 | Future Research

For future research, it would be beneficial to incorporate sustainability factors into the evaluation framework. Additionally, integrating various wheat qualities into the model could enhance the realism of the findings and more accurately reflect real-world conditions. Further, expanding the SC network to involve additional facilities at multiple echelons could culminate in long-term cost savings by lowering both tactical and operational expenditures, thereby improving the overall efficiency of the SC.

Due to specific constraints in the current study, facilities were hypothetically centralized within provincial capitals. For future research, it would be advantageous to investigate shorter time intervals and disaggregate the study into more specific geographical units, such as individual provinces or municipalities. This approach would enhance the practical applicability of the research and yield more valuable insights for real-world implementation, thereby facilitating the crucial transition from theoretical frameworks to practical solutions.

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## Data Availability

Sufficient data is available upon request.

## Conflict of Interest

No potential conflict of interest was reported by the authors.

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