



## Multi-Objective Optimization of a Sustainable Wheat Supply Chain: Reducing Waste, Costs, and Environmental Impact

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### Abstract

Wheat is one of the most essential crops and plays a critical role in global food security. Therefore, effective management across all stages of the wheat supply chain is vital. This study presents a sustainable wheat supply chain model that integrates economic, environmental, and social considerations. A mixed-integer linear programming (MILP) model is developed to minimize wheat loss and waste while optimizing key sustainability objectives. Economically, the model aims to reduce total supply chain costs, including those related to production, storage, transportation, and facility establishment. Environmentally, it seeks to reduce greenhouse gas emissions, while socially, it strives to enhance job opportunities through the development of new facilities. The model incorporates elements such as animal feed centers and facilities for waste collection, recovery, and disposal. It also accounts for losses during harvesting, transportation, and processing. The multi-objective epsilon-constraint method was employed to solve the model and analyze the impact of various parameters. Using real data from Isfahan Province, Iran, the results show that wheat waste can be reduced from 25,000 to 7,000 tons by upgrading harvesting machinery. Additionally, by reducing transportation losses to meet global standards and lowering bread waste by 1%, the province could save 15,000 tons of wheat. The model also supports the construction of one new silo and one waste collection center, which would create a considerable number of jobs. These findings highlight the role of sustainable supply chain design in mitigating food loss, improving resource efficiency, and enhancing long-term food security. The study offers valuable insights for policymakers and industry stakeholders, emphasizing the importance of integrating sustainability measures into supply chain management.

**Keywords:** wheat supply chain, sustainability, food wastage, mixed integer linear programming.

**Paper Type:** Original Research

### 1. Introduction

In addition to being vital for human health, food is considered one of the world's most important environmental and economic factors. Therefore, if the food supply chain is disrupted, many problems can arise (Azani et al., 2022). Because of the rising global population, the need for food security is being increasingly felt, and the importance of this issue is particularly significant when it comes to perishable foods (Nikounam Nezami et al., 2024). Food security generally refers to the access of all members of a society to sufficient and nutritious food for a healthy and active life, and it is usually considered in a way that both physical access and economic ability to obtain wholesome food products are considered (Mogale, Kumar, Kumar, et al., 2018). On the other hand, the Food and Agriculture Organization (FAO) states that about one-third of food products are lost through waste and food waste, which can significantly lead to the loss of resources such as land, water, labor, energy, and money (Hellegers, 2022; Mogale, Kumar, Kumar, et al., 2018). According to the FAO definition, "food loss" is considered for consumption and distribution stages, while the term "food waste" is considered for other stages of the food supply chain (Gustavsson et al., 2011). Of course, some researchers have introduced the waste of resources in all stages of the supply chain as food waste (Do et al., 2021; FAO, 2019). Traditional storage methods, poor cooperation between members of the supply chain, and lack of suitable infrastructure for transportation are among the most important causes of food wastage and loss. In this regard, one of the new concepts that has recently attracted the attention of researchers is the concept of supply chain sustainability. The world today is facing issues such as climate change, drought, worn-out soil, various types of pollution, and the emission of greenhouse gases. In this situation, the question that arises is how human life can be improved by considering the limitation of natural resources and with less destruction of the environment. In the report of the World Commission on Environment and Development, Brundtland and colleagues provided the answer to this question using the concept of sustainability. According to Brundtland's report,

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"Sustainability is a solution to meeting the needs of the present without compromising the ability of future generations to meet their own needs" (La Londe & Masters, 1994). Given that a crucial portion of households' food requirements, particularly in developing countries, is met through wheat and its products (flour and bread), designing a stable and efficient supply chain for them holds immense significance. In this regard, this research aims to create a comprehensive model of the wheat supply chain to reduce loss and wastage. This involves addressing economic aspects by minimizing costs, including transportation costs, production, maintenance, etc. Additionally, the model targets environmental goals by reducing greenhouse gas emissions. Moreover, from a social perspective, the research seeks to increase job opportunities by establishing new facilities. It is worth noting that although the economic aspect remains undeniably important, greenhouse gas emissions and social impacts have increasingly attracted the attention of sustainability researchers and are now considered fundamental pillars of sustainability (Khorshidvand et al., 2021c). The wheat supply chain in Iran has four primary levels; suppliers, silos, flour factories, and clients. Wheat is produced in different seasons and various regions of Iran. But the produced wheat is usually not enough to meet the needs of the whole country, and this shortage is solved through imports, and it enters the silos with the transport fleet. After sleeping in silos, wheat is ready to be milled and sent to flour mills. The flour of bakeries, confectioneries, and other related industries is produced and distributed to them in these factories. This research has tried to pay attention to all the essential levels of the wheat supply chain and include them in the modeling. Although wheat wastage happens in different stages, the main part of the wastage is related to the wheat harvesting stage. The loss of wheat during harvesting can be due to the fall of cereal grains, which occurs both in manual harvesting and in harvest with a combined harvester, which has been considered in this research. In addition, since the wheat produced in Iran is generally transported in bulk and using road transport such as Nissan, truck, and trailer, and imported wheat is transported by train, a large part of it is lost in these movements. From this, Mogale et al. (Mogale, Ghadge, et al., 2020) divided the grain into bulk and bag categories. They calculated grain wastage in the transportation stage, but the moving distance was neglected in this calculation, which is included in the present study. On the other hand, since the main consumption of wheat is related to the production of bread, bread waste, which includes most of the waste, has been discussed in this research. Also, during the conversion of wheat into flour, straw and leaves separated from wheat, along with bread scraps, can be used as animal feed, which is also included in this model. Among the research done, only Hosseini-Motlagh et al. (Hosseini-Motlagh et al., 2021) addressed the issue of bread waste and turned it into animal feed. However, in the current research, with the collected field data, this cycle has been completed to be more similar to the real world. In addition to bread waste collection centers, animal food centers, recovery centers, and disposal centers are also seen in the model. In general, this research tried to achieve a sustainable design of the supply chain of this strategic product by taking into account the simultaneous and integrated wastage and waste in different parts of the wheat supply chain. The main contribution of this research is the development of a comprehensive and sustainable mixed-integer linear programming (MILP) model for designing the wheat supply chain, which simultaneously addresses economic (cost reduction), environmental (greenhouse gas emission reduction), and social (job creation) objectives. The innovation of this model lies in its integration of animal feed centers, waste collection, recovery, and disposal facilities, as well as its detailed consideration of wheat losses at various stages of the supply chain—from harvesting to transportation and processing. The significance of this study stems from its use of real-world data from Isfahan province to evaluate the model's effectiveness, demonstrating its considerable potential for reducing waste and enhancing the sustainability of the wheat supply chain. The organization of this research is as follows: In the second part, an overview of past papers on the sustainable supply chains of wheat and grains is presented. The problem characterization and its mathematical model are presented in the third part. The solution method is introduced in the fourth part, and the relevant case study is introduced in the fifth part. The computational results and the sensitivity analysis are provided in the sixth and seventh sections, respectively. Finally, the eighth section is devoted to conclusions and suggestions for future studies.

## 2. Literature Review

Designing an appropriate supply chain network, while ensuring favorable economic, environmental, and social conditions, is one of the most critical and influential factors in achieving a sustainable supply chain (Khorshidvand et al., 2021b). In this regard and according to different sustainability dimensions, various studies in the field of sustainable supply chains of wheat and grains have been categorized as one-dimensional, two-dimensional, and three-dimensional problems, whose overview is shown in Tables 1 and 2. Table 1 shows the studies carried out regarding mathematical models and solution methods. Table 2 illustrates the details of the objective functions and the different dimensions of stability, followed by a brief explanation of these problems.

Table 1. Review of wheat and grain studies according to mathematical model and solution method

Article	Time period		Modeling	Solution method	Objective functions		Objectives
	Single	Multi			Single	Multi	
<i>One-dimensional problems</i>							
Asgari et al. (2013)	✓	-	LIP	Genetic Algorithm (GA)	✓	-	Minimizing total cost
Nourbakhsh et al. (2016)	✓	-	MILP	Benchmarking	✓	-	Minimizing total cost
Gholamian and Taghanzadeh (2017)	-	✓	MILP	Cplex	✓	-	Minimizing total cost
Mogale et al. (2017)	-	✓	MINLP	Chemical Reaction Optimization combined with Tabu Search (CROTS)	✓	-	Minimizing total cost
Mogale et al. (2018)	-	✓	MINLP	NCRO creat of CRO and NSGA-II	✓	-	Minimizing total cost Minimizing total lead time
Mogale et al. (2018b)	-	✓	MINLP	Hybrid Particle-Chemical Reaction Optimization (HP-CRO) algorithm	✓	-	Minimizing total cost
Naderi et al. (2020)	-	✓	MILP	Benders decomposition	✓	-	Minimizing total cost
Pourmohammadi et al. (2020)	-	✓	MILP	Scenario-based Stochastic programming	✓	-	Minimizing total cost
Trisna et al. (2020)	✓	-	FMILP	NSGA-II	✓	-	Minimizing total cost Maximizing product quality, reliability and local flour usage
Hosseini-Motlagh et al. (2021)	-	✓	MILP	Cplex, Robust strategic and tactical decisions	✓	-	Minimizing total cost
Dundar et al. (2022)	-	✓	MILP	Cplex	✓	-	Minimizing total cost
<i>Two-dimensional problems</i>							
Banasik et al. (2017)	-	✓	MILP	Epsilon Constraint	-	✓	Maximizing of profit over the planning horizon Minimizing total energy
Mogale et al. (2020c)	-	✓	MILP	Cplex, PSO, GLNPSO	✓	-	Minimizing total cost
Mogale et al. (2020b)	✓	-	MILP	Cplex, NK Hybrid Genetic Algorithm (NKHGA)	✓	-	Minimizing total cost
Mogale et al. (2020a)	-	✓	MILP	Composition Multi-Objective Particle Swarm Optimisation (MOPSO) and (NSGA-II)	-	✓	Minimizing total cost Minimizing carbon dioxide emissions
Hosseini-Motlagh et al. (2020)	-	✓	MINLP	Hybrid Stochastic Fuzzy-Robust programming	✓	-	Minimizing total cost Minimizing of non-resiliency in the whole network Minimizing negative impacts of social responsibility
Sharma et al. (2021)	-	✓	MILP	Cplex, K-means clustering	✓	-	Minimizing total cost
<i>Three-dimensional problems</i>							
Allaoui et al. (2018)	-	✓	MILP	Cplex, Analytic Hierarchy Process (AHP) method and the Ordered Weighted Averaging (OWA)	-	✓	Minimizing total cost Minimizing carbon dioxide emissions and total water consumption Minimizing the number of closed jobs
Motevalli-Taher et al. (2020)	-	✓	MILP	Meta-goal programming	-	✓	Minimizing total cost Minimizing water consumption Maximizing obtained job opportunity
Yousefi-Babadi et al. (2022)	✓	-	LP	A hybrid GIS-BWM approach	-	✓	Optimization in wheat storage centers
Mogale et al. (2023)	-	✓	MINLP	MOGLNPSO and MOPSO	-	✓	Minimizing total cost Minimizing of CO2 emission Maximizing of social benefits
<b>This paper</b>	-	✓	MILP	Cplex-Epsilon Constraint	-	✓	Minimizing total cost Minimizing carbon dioxide emissions and loss in harvest mode Maximizing job opportunities created

**Table 2.** Review of wheat and cereal studies according to sustainability dimensions

Article	Sustainability			Details of the objective function													
				economic								environmental				social	
	Economic	Environmental	Social	FTC	VTC	FHC	VHC	FPC	VPC	CPCC	LTC	CD	CDC	CW	LH	JC	JL
<i>One-dimensional problems</i>																	
Asgari et al. (2013)	✓	-	-	-	✓	-	✓	-	-	-	-	-	-	-	-	-	-
Nourbakhsh et al. (2016)	✓	-	-	-	✓	-	-	-	-	✓	-	-	-	-	-	-	-
Gholamian and Taghanzadeh (2017)	✓	-	-	-	✓	-	✓	-	-	✓	-	-	-	-	-	-	-
Mogale et al. (2017)	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	-	-
Mogale et al. (2018)	✓	-	-	-	✓	-	✓	-	-	✓	-	-	-	-	-	-	-
Mogale et al. (2018b)	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	-	-
Naderi et al. (2020)	✓	-	-	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-
Pourmohammadi et al. (2020)	✓	-	-	-	✓	-	✓	-	-	✓	-	-	-	-	-	-	-
Trisna et al. (2020)	✓	-	-	-	✓	-	✓	-	✓	-	-	-	-	-	-	-	-
Hosseini-Motlagh et al. (2021)	✓	-	-	-	✓	-	✓	-	✓	✓	-	-	-	-	-	-	-
Dundar et al. (2022)	✓	-	-	-	✓	-	✓	-	-	-	-	-	-	-	-	-	-
<i>Two-dimensional problems</i>																	
Banasik et al. (2017)	✓	✓	-	-	-	-	✓	-	✓	-	-	-	✓	-	-	-	-
Mogale et al. (2020c)	✓	-	-	-	✓	-	✓	-	✓	✓	✓	-	✓	-	-	-	-
Mogale et al. (2020b)	✓	✓	-	✓	✓	-	-	-	-	✓	-	-	✓	-	-	-	-
Mogale et al. (2020a)	✓	✓	-	✓	✓	-	✓	-	-	✓	-	✓	-	-	-	-	-
Hosseini-Motlagh et al. (2020)	✓	-	✓	-	✓	-	✓	-	-	✓	-	-	-	-	-	✓	✓
Sharma et al. (2021)	✓	✓	-	✓	✓	-	-	-	-	-	-	-	✓	-	-	-	-
<i>Three-dimensional problems</i>																	
Allaoui et al. (2018)	✓	✓	✓	-	✓	-	✓	-	✓	-	-	✓	-	✓	-	✓	✓
Motevalli-Taher et al. (2020)	✓	✓	✓	-	✓	-	✓	-	✓	✓	-	-	-	✓	-	✓	✓
Yousefi-Babadi et al. (2022)	✓	✓	✓	-	✓	-	✓	-	-	✓	-	✓	-	✓	-	✓	✓
Mogale et al. (2023)	✓	✓	✓	-	✓	-	✓	-	✓	✓	-	✓	-	-	-	✓	-
<b>This paper</b>	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Fixed Transport Cost: FTC, Variable Transport Cost: VTC, Fixed Holding Cost: FHC, Variable Holding Cost: VHC, Fixed Production Cost: FPC  
 Variable Production Cost: VPC, Creating Potential Centers Cost: CPCC, Loss Transport Cost: LTC  
 Carbon Dioxide: CD, Carbon Dioxide Cost: CDC, Consuming Water: CW, Loss in Harvest: LH  
 Job Created: JC, Job Lost: JL

**2.1. One-Dimensional Sustainability Problems in Wheat and Grain Supply Chains**

One-dimensional problems only pay attention to the economic dimension and try to minimize the supply chain costs. Among the research conducted on these problems, we can mention the research of Asgari et al. (Asgari et al., 2013). The problem investigated in this research is that according to the availability of the quantities of wheat produced in various months, the fixed monthly needs of the provinces are met, and a pervasive plan for storing and distributing wheat and a model for reducing costs in storage and prioritizing maintenance are provided. Nourbakhsh et al. (Nourbakhsh et al., 2016) presented a model to minimize post-harvest grain wastage in the relevant supply chain network. They proposed a logistic model for transporting grains and investing in infrastructure by identifying optimal locations for facilities and optimizing the capacity of roads and especially railways. Next, Gholamian and Taghanzadeh (Gholamian & Taghanzadeh, 2017) addressed the supply chain network by considering the two dimensions of strategic and tactical. In the strategic dimension, choosing the supplier, the optimal location of new silos and storage centers, and in the tactical dimension, the optimal amounts of wheat import, the transportation of imported and domestic wheat, wheat storage, and the production of various wheat products are discussed. Mogale et al. (Mogale et al., 2017) investigated the transportation and storage problems of bulk wheat in India's public distribution system. They found that if done in principle, bulk transportation and storage can significantly reduce wheat wastage during transportation and storage, resulting in significant cost savings. They presented a multi-level and multi-period model to minimize transportation, storage, and operational costs in the Indian wheat supply chain. Mogale et al. (Mogale, Kumar, Kumar, et al., 2018) presented a multi-objective multi-period integrated optimization model for the silo location-allocation problem. In another research, considering that the Indian government is creating modern infrastructure for the transportation system of food grains and their storage, Mogale et al. (Mogale, Kumar, & Tiwari, 2018) modeled the movement and storage of food grains, considering seasonal purchases, silo capacity, satisfaction demand centers, and vehicle capacity constraints were presented. Due to insufficient wheat production in Iran, Naderi et al. (Naderi et al., 2020) introduced

this country as a wheat importer whose distribution network is strategic and costly. They presented a model to reduce the costs of setting up distribution centers and the optimal allocation of suppliers and customers to distribution centers. In this regard and considering that the majority of wheat imports in Iran are carried out through northern and southern ports and the storage of imported wheat is very important, Pourmohammadi et al. (Pourmohammadi et al., 2020), by presenting a model, the difference between the short-term and long-term storage capacity of wheat with the aim reduced the total of the network costs. In this study, the redesign of the network and planning according to the problems of supplier selection, storage, transportation, and distribution, as well as the capacity of new storage facilities, have been discussed. Since traditional and modern food industries (such as noodles, biscuits, dry bread, noodles, etc.) in Indonesia are mainly based on wheat flour, so far, much research has been conducted on local Indonesian flour as a substitute for wheat flour. Among these researches, we can refer to Trisna et al. (Trisna et al., 2020), who found that this alternative has investigated various conflicts and problems in the relevant supply chain with an optimization approach. Hosseini-Motlagh et al. (Hosseini-Motlagh et al., 2021) presented a wheat supply chain that includes the production, collection, and distribution of this product. Dündar et al. (Dündar et al., 2022) presented a multi-product, multi-period, multi-stage, and multi-transportation model regarding the structure of the Turkish wheat supply chain. This model optimized the total number of vehicle trips, reduced total transportation costs, and determined vehicles with the appropriate capacity to transport wheat in the relevant supply chain.

## 2.2. Two-dimensional Sustainability Problems in Wheat and Grain Supply Chains

The two-dimensional problems have been investigated in economic-environmental and economic-social categories, which will be discussed further. Banasik et al. (Banasik et al., 2017) proposed an optimization model for different methods of dealing with waste in food supply chains, such as prevention, recycling, and waste disposal. Within this model, the supply chain's environmental performance is represented by the exergy analysis index, which can also represent other widely used metrics like fuel and energy consumption and the quantity of waste generated in a single value. Owing to India's steady rise in wheat production over the past few decades, the storage capacity of wheat in this country has become very important. For this purpose, In the main states that produce and consume wheat, the Indian government is building multiple silos to reduce the huge gap between storage capacity and food grain availability. In this regard, Mogale et al. (Mogale, Kumar, et al., 2020) focused on the design of the food supply chain network that includes strategic and tactical levels and presented a model for it. At the same time, this model optimally determines the number of established silos, the amount of transportation and storage, the amount of wastage in transportation, and the number of vehicles with different capacities. In another study, Mogale et al. (Mogale, Ghadge, et al., 2020) developed a food supply chain model to help with the effective procurement of grains in India and the best possible allocation of shopping center locations and numbers. Further, Mogale et al. (Mogale, Cheikhrouhou, et al., 2020) presented a bi-objective optimization model for a sustainable food grain supply chain distribution system to decide on the optimal locations of central, state, and regional warehouses and planning and storage in a multi-period environment. Hosseini-Motlagh et al. (Hosseini-Motlagh et al., 2020), with a multi-objective mathematical model, redesigned the wheat supply chain network, including several suppliers, existing silos, flour factories, and demand areas in an uncertain environment. In this model, they considered social impact and resilience as two important and necessary aspects of food supply chains at the same time. Bhardwaj et al. (2023) investigated the issue of bread waste in the supply chain, with a particular focus on the Indian bakery industry. The study identified key causes of wastage through a systematic literature review and pilot studies, which were further analyzed using Monte Carlo simulation techniques. One of the critical insights of the study is the recommendation to reduce bread's market exposure from six days to three, based on successful strategies implemented by two companies. This approach ensures that any returned bread remains in good condition, allowing an additional two to three days for its conversion into by-products – thus promoting waste valorization. Bhardwaj and colleagues emphasize that employing such waste-utilization strategies not only reduces economic losses but also contributes to sustainable practices by minimizing environmental impact. Since COVID-19 was able to cause significant disruptions in the supply chain of food grains because of quarantine, Sharma et al. (Sharma et al., 2024) focused on social distancing in the process of purchasing wheat. In this problem, it is assumed that only a limited number of farmers are allowed to bring their products to the shopping centers every day, and the distance between agricultural fields and shopping centers should be the smallest possible value, which is determined using the k-means clustering method. For this problem, the researchers presented a mixed integer programming model to minimize transportation costs.

### 2.3. Three-dimensional Sustainability Problems in Wheat and Grain Supply Chains

Simultaneously addressing the three dimensions of sustainability – economic, environmental, and social – is inherently challenging and has been explored from various perspectives across different problem domains. For instance, Khorshidvand et al. (2021a) proposed a sustainable closed-loop supply chain network with three objective functions, each corresponding to a different dimension of sustainability: the first aims to maximize the total profit of the supply chain, the second seeks to minimize overall CO<sub>2</sub> emissions, and the third focuses on enhancing social responsibility. The topic of three-dimensional sustainability issues in wheat and grain supply chains has received limited attention and will be explored further in the following discussion. Allaoui et al. (Allaoui et al., 2018) proposed a two-stage hybrid approach to design a sustainable wheat supply chain. The first stage includes evaluating potential suppliers, transportation centers, and distribution centers with different criteria and sub-criteria to specify their efficiency. Using the results acquired from the first stage, a multi-objective optimization model is presented to optimize the design of the supply chain network in the second stage. Motevalli-Taher et al. (Motevalli-Taher et al., 2020) considered the sustainable supply chain of wheat from farm to final consumption, including farms, silos, flour factories, and clients. They presented a multi-objective, multi-product, multi-cycle mathematical model to minimize network costs and consumption of water and maximize employment opportunities. The proposed model predicts the non-deterministic demand for wheat flour for each customer through simulation. Formentini et al. (2022) address the limited understanding of effective strategies for managing food loss and waste (FLW) through the lens of circular supply chain management. Their study highlights the importance of integrating the FLW Reporting and Accounting Standard as a systematic means of identifying, measuring, and repurposing FLW throughout the agri-food supply chain. The authors approach the issue from a circular economy perspective, emphasizing the relevance of waste hierarchies and the application of the 3R and 4R principles (reduce, reuse, recycle, and recover). A significant contribution of the study lies in its in-depth analysis of Barilla's soft wheat bread supply chain. By collecting and analyzing both qualitative and quantitative data, the authors examine how the FLW Standard can be effectively implemented. They identify key enablers and obstacles in measuring food loss and waste, while also offering a standardized tool to support sustainable FLW practices. Their findings reveal that Barilla's supply chain serves as a strong example of circular management, where minimal waste is generated and the value of resources is preserved through systematic reuse. Yousefi-Babadi et al. (Yousefi-Babadi et al., 2022) provided a new definition for the sustainable relocation of facilities and, using existing national and international reports, identified criteria and sub-criteria for it and weighted them using the best-worst method. Then, each region was given a value as a sustainable logistics value. Finally, the affected areas were ranked to identify the best candidates for a sustainable relocation. The results showed that Iran is in an extremely satisfactory situation regarding moving wheat storage facilities. In another study, Mogale et al. (Mogale et al., 2023) proposed a model for the simultaneous optimization of sustainability goals and decisions, such as determining the location and capacity of basic, field, and regional silos, the allocation between different levels of the supply chain, the number of different vehicles and the capacity used. In this research, they evaluated the relationships between changes in supply, demand, and capacity of silos with the defined goals. The authors showed that the amount of demand compared to the capacity of supply and capacity of silos significantly affects the economic and environmental goals. In summary, the reviewed research shows that developing a stable and efficient supply chain for a strategic product like wheat – while minimizing waste and wastage at every stage – presents a viable solution for mitigating harmful environmental impacts and enhancing social and cultural conditions alongside economic benefits. This research has been conducted in this direction, and the following sections will highlight some of its key aspects

### 3. Problem description

The current research seeks to design a complete network of the wheat supply chain, from the time of wheat harvesting to its distribution and consumption, where lost and waste are considered in an integrated manner in all stages of this chain. It should be noted that wheat is grown in two ways, irrigated and dry, in Iran's farms. The irrigated wheat is usually harvested with a combine harvester, but in some areas, wheat can also be grown in a dry manner. Wheat harvesting can only be done with a sickle if these areas are inaccessible. At the time of harvesting wheat in both mentioned methods (using a combined machine and manually), we see the waste of this product due to various reasons. During transportation, due to the lightness of the wheat and the vehicles not being completely covered, a volume of wheat is lost, and in this research, we have tried to pay attention to these issues. In addition, in this research, the stages of returning the waste products produced from wheat (especially bread),

including recovery centers and disposal centers, have also been discussed. In the recovery centers, a part of the imported waste is turned into fertilizer, and another part is sent to the animal feed centers as livestock and poultry feed. However, in disposal centers, unrecoverable waste is buried underground. In supplying the needed wheat, although the priority is to cultivate wheat inside the country, it is usually not responsive, and its deficiency is met through imports. For importing wheat, there are several suppliers, but imported wheat is only transferred to silos that have rail transportation. In domestic production, because there are different farms with different cultivation capacities and the government generally purchases the harvested wheat, government shopping centers with different capacities have been considered in this research. In addition, due to the growing need of the country and the increasing consumption of this product, potential places for building new silos and also potential places for creating new waste collection centers have been considered, the creation of which, in addition to economic and environmental effects, can create new job opportunities, have significant social effects as well. In fact, in this research, the problem has been addressed from various aspects of sustainability, and in this regard, a multi-level and multi-product model has been presented, and an overview of the problem investigated in this research is shown in Figure 1.

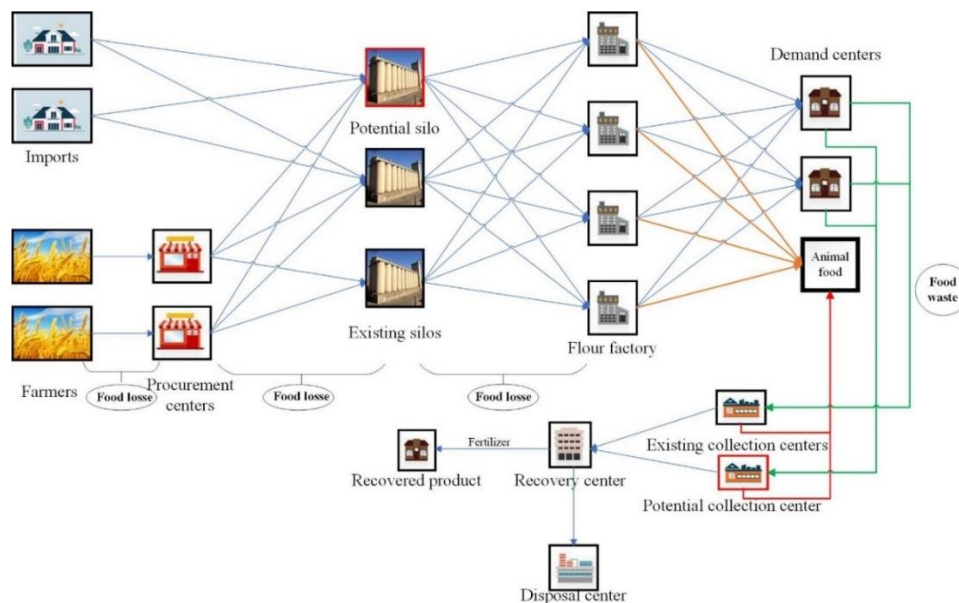


Figure 1. Schematic view of the present problem.

## Assumptions

- Farms and shopping centers are included regionally.
- Wheat is sent from the wheat cultivation areas (farms) to the shopping centers of the same area.
- Irrigated crops are harvested with a combine harvester, and dry crops are harvested with a sickle.
- A deficiency of wheat is not allowed.
- Safety storage in silos is considered for wheat.
- The shortage of wheat is solved through imports.
- The transfer fee depends on the vehicle type and is affected by the distance between the origin and destination.
- The potential locations of silos and waste collection centers are known.
- The production capacity of flour factories is known.
- Wheels are supplied internally (producer) and externally (import).
- Harvesting machine settings are done well.
- The demand for flour is considered according to the type of flour and for bread production.
- In the recovery cycle, only bread waste is considered.

- The fuel used by diesel vehicles is considered for carbon dioxide emission.
- Wheat is imported to silos by train and transported between chain levels by truck and trailer.
- In the province, it is possible to build a maximum of one potential new silo and a waste collection center.

**The mathematical model sets are as follows:**

Sets

$I$	Foreign suppliers
$B$	Wheat fields
$L$	Guaranteed shopping centers
$S$	Existing silos
$S'$	Potential silos (new) to build
$F$	Flour factories
$C$	Demand centers
$M$	Waste collection centers
$M'$	Potential (new) waste collection centers to create
$D$	disposal centers
$R$	Recovery centers
$T$	periods
$P$	Wheat products (types of flour)
$V$	vehicles
$E$	Demand centers for the recovered product (fertilizer)

**The mathematical model sets are as follows:**

Parameters

Transportation costs	$T_{cx,y,v,t}$	The transporting cost of each ton of product (wheat, flour, bread waste, fertilizer) from facility $x$ to facility $y$ by vehicle $v$ in period $t$
	FTC	The transportation fix cost
The amount of harvesting, and waste of wheat	$T_{cw}$	Lost cost per ton of wheat
	$L_{cv}$	The amount of lost per ton of wheat transported by vehicle $v$ in one unit of distance
	$p_{wr}$	The percentage of waste that is turned into fertilizer at the recovery center $r$
	$Conb$	The percentage of combined machine waste in harvesting each ton of wheat
	$W_{das}$	Percentage of sickle harvesting waste per ton of wheat
	$B_{wb,t}$	Cultivable land for irrigated wheat in field $b$ in hectares in period $t$
	$B_{db,t}$	Cultivable land for dry wheat in field $b$ in hectares in period $t$
	$W_{gb,t}$	The minimum amount of tons of wheat grown by the irrigation method per hectare in field $b$ in period $t$
	$W_{db,t}$	The minimum amount of tons of wheat grown by dry method per hectare in field $b$ in period $t$
	The cost of creating potential centers	$Y_{S_s'}$
$Y_{m_{m'}}$		The cost of creating a new collection center (potential) $m'$
Production costs	$pc_{p,f}$	The production cost of flour $p$ in the factory $f$

	$P_{rr}$	The fertilizer production cost in the recovery center $r$
	FPC	The production fixed cost in a flour factory
	FPR	The production fixed cost in a recovery center
Holding cost	Chx	The holding cost of each ton of products (wheat, flour, waste bread, and fertilizer) in the facility $x$
	FHC	The holding fix cost
The amount of CO2 generated	Cov	The amount of CO2 generated per unit distance traveled by the vehicle $v$
Job opportunities	$Jo_{s'}$	The fixed number of job opportunities created from the construction of a new silo (potential) $s'$
	$Jo_{m'}$	The fixed number of job opportunities created from the establishment of a new (potential) collection center $m'$
Demand	$D_{pp,c,t}$	Demand for flour $p$ by demand center $c$ in period $t$
	$D_{ff,t}$	Demand for wheat by flour factory $f$ in period $t$
	$D_{oe,t}$	Demand for fertilizer by customer $e$ in period $t$
Capacities	Capesf	Maximum capacity of import to the province
	$Cap_{x,t}$	The capacity of facility $x$ in period $t$
	Capv	The capacity of vehicle $v$
Distances	$Dis_{x,y}$	Average distance from facility $x$ to facility $y$
	$\beta_p$	Conversion coefficient of wheat into flour $p$
Other parameters	$\theta_p$	The coefficient of stem and leaf separated from wheat (straw) $p$
	$\lambda_p$	The percentage allocated to convert wheat into flour $p$
	$\mu$	Conversion coefficient of waste to animal feed
	SSa	Wheat safety stock
	U	A large enough number
	Wt	Waste percentage
	$\omega$	Fertilizer conversion factor
	pbp	Conversion coefficient of flour $p$ to types of bread
	Needt	The whole province's need for wheat in period $t$

#### Decision variables

Following is a definition of the problem's decision variables:

Binary variables	$SS_{s'}$	1 If a new (potential) silo $s'$ is built, and 0 otherwise
	$Sm_{m'}$	1 If a new (potential) collection center $m'$ is built, and 0 otherwise
	$Al_{x,y}$	1 If facility $x$ is assigned to facility $y$ , and 0 otherwise
Continuous variables	$US_{v,x,y,t}$	Amount of product (wheat, flour, bread waste, and fertilizer) transported in tons by vehicle $v$ from facility $x$ to facility $y$ in period $t$
	$US_{wv,x,t}$	Amount of bread waste transported in tons by vehicle $v$ from facility $x$ to the animal feed center in period $t$
	$Prof_{p,t}$	Amount of flour $p$ produced in the flour factory $f$ in period $t$

	$Inv_{x,t}$	Product inventory level (wheat, flour, and bread waste) held in facility x in period t
	$Flx_{y,t}$	The amount of wheat that is wasted in transportation from facility x to facility y in period t
	$HAb,t$	The amount of wheat that can be harvested per hectare of field b with the irrigation method in period t
	$HDb,t$	The amount of wheat that can be harvested per hectare of field b with the dry method in period t
Integer variables	$VV_{v,x,y,t}$	Number of vehicles v used for transportation from facility x to facility y in period t

### Mathematical model

The mathematical model is divided into two categories of constraints and objective functions:

Objective functions

$$\text{Min}Z_1 = Z_{1-1} + Z_{1-2} + Z_{1-3} + Z_{1-4} + Z_{1-5} + Z_{1-6} + Z_{1-7} + Z_{1-8} \quad (1)$$

$$Z_{1-1} = \sum_{s'=1}^{S'} (SS_{s'} \times ys_{s'}) + \sum_{m'=1}^{M'} (Sm_{m'} \times ym_{m'}) \quad (1-1)$$

$$\begin{aligned} Z_{1-2} = & \sum_{v=1}^V \sum_{t=1}^T \sum_{s=1}^S \sum_{i=1}^I Tc_{i,s,v,t} \times Dis_{i,s} \times US_{v,i,s,t} + \sum_{v=1}^V \sum_{t=1}^T \sum_{s'=1}^{S'} \sum_{i=1}^I Tc_{i,s',v,t} \times Dis_{i,s'} \times US_{v,i,s',t} \\ & + \sum_{v=1}^V \sum_{t=1}^T \sum_{b=1}^B \sum_{l=1}^L Tc_{b,l,v,t} \times Dis_{b,l} \times US_{v,b,l,t} + \sum_{v=1}^V \sum_{t=1}^T \sum_{s=1}^S \sum_{l=1}^L Tc_{l,s,v,t} \times Dis_{l,s} \times US_{v,l,s,t} \\ & + \sum_{v=1}^V \sum_{t=1}^T \sum_{s'=1}^{S'} \sum_{f=1}^F Tc_{l,s',v,t} \times Dis_{l,s'} \times US_{v,l,s',t} + \sum_{v=1}^V \sum_{t=1}^T \sum_{s=1}^S \sum_{f=1}^F Tc_{s,f,v,t} \times Dis_{s,f} \times US_{v,s,f,t} \\ & + \sum_{v=1}^V \sum_{t=1}^T \sum_{s'=1}^{S'} \sum_{f=1}^F Tc_{s',f,v,t} \times Dis_{s',f} \times US_{v,s',f,t} + \sum_{v=1}^V \sum_{t=1}^T \sum_{c=1}^C \sum_{p=1}^P \sum_{f=1}^F Tc_{f,c,v,t} \times Dis_{f,c} \times US_{v,f,c,p,t} \\ & + \sum_{v=1}^V \sum_{t=1}^T \sum_{c=1}^C \sum_{m=1}^M Tc_{c,m,v,t} \times Dis_{c,m} \times US_{v,c,m,t} + \sum_{v=1}^V \sum_{t=1}^T \sum_{c=1}^C \sum_{m'=1}^{M'} Tc_{c,m',v,t} \times Dis_{c,m'} \times US_{v,c,m',t} \\ & + \sum_{v=1}^V \sum_{t=1}^T \sum_{m=1}^M \sum_{r=1}^R Tc_{m,r,v,t} \times Dis_{m,r} \times US_{v,m,r,t} + \sum_{v=1}^V \sum_{t=1}^T \sum_{m'=1}^{M'} \sum_{r=1}^R Tc_{m',r,v,t} \times Dis_{m',r} \times US_{v,m',r,t} \\ & + \sum_{v=1}^V \sum_{t=1}^T \sum_{d=1}^D \sum_{r=1}^R Tc_{r,d,v,t} \times Dis_{r,d} \times US_{v,r,d,t} + \sum_{v=1}^V \sum_{t=1}^T \sum_{r=1}^R \sum_{e=1}^E Tc_{r,e,v,t} \times Dis_{r,e} \times US_{v,r,e,t} \\ & + \sum_{v=1}^V \sum_{t=1}^T \sum_{m=1}^M Tcw_{m,v,t} \times Dis_m \times USw_{v,m,t} + \sum_{v=1}^V \sum_{t=1}^T \sum_{m'=1}^{M'} Tcw_{m',v,t} \times Dis_{m'} \times USw_{v,m',t} \\ & + \sum_{v=1}^V \sum_{t=1}^T \sum_{f=1}^F Tcw_{f,v,t} \times Dis_f \times USw_{v,f,t} \end{aligned} \quad (1-2)$$

$$\begin{aligned} Z_{1-3} = & \text{FTC} \times \left( \sum_{l=1}^L \sum_{b=1}^B Al_{b,l} + \sum_{l=1}^L \sum_{s=1}^S Al_{l,s} + \sum_{l=1}^L \sum_{s'=1}^{S'} Al_{l,s'} + \sum_{s=1}^S \sum_{f=1}^F Al_{s,f} + \sum_{s'=1}^{S'} \sum_{f=1}^F Al_{s',f} + \right. \\ & \left. \sum_{c=1}^C \sum_{m=1}^M Al_{c,m} + \sum_{c=1}^C \sum_{m'=1}^{M'} Al_{c,m'} + \sum_{m=1}^M \sum_{r=1}^R Al_{m,r} + \sum_{m'=1}^{M'} \sum_{r=1}^R Al_{m',r} + \sum_{r=1}^R \sum_{d=1}^D Al_{r,d} + \sum_{r=1}^R \sum_{e=1}^E Al_{r,e} + \right. \\ & \left. \sum_{f=1}^F \sum_{c=1}^C Al_{f,c} + \sum_{i=1}^I \sum_{s=1}^S Al_{i,s} + \sum_{i=1}^I \sum_{s'=1}^{S'} Al_{i,s'} \right) \end{aligned} \quad (1-3)$$

$$Z_{1-4} = \sum_{s'=1}^{S'} \sum_{t=1}^T \text{Ch}_{s'} \times \text{Inv}_{s',t} + \sum_{s=1}^S \sum_{t=1}^T \text{Ch}_s \times \text{Inv}_{s,t} + \sum_{f=1}^F \sum_{t=1}^T \text{Ch}_f \times \text{Inv}_{f,t} + \sum_{m=1}^M \sum_{t=1}^T \text{Ch}_m \times \text{Inv}_{m,t} + \sum_{m'=1}^{M'} \sum_{t=1}^T \text{Ch}_{m'} \times \text{Inv}_{m',t} + \sum_{r=1}^R \sum_{t=1}^T \text{Ch}_r \times \text{Inv}_{r,t} \quad (1-4)$$

$$Z_{1-5} = \text{FHC} \times \left( \sum_{l=1}^L \sum_{s=1}^S \text{Al}_{l,s} + \sum_{l=1}^L \sum_{s'=1}^{S'} \text{Al}_{l,s'} + \sum_{s=1}^S \sum_{f=1}^F \text{Al}_{s,f} + \sum_{s'=1}^{S'} \sum_{f=1}^F \text{Al}_{s',f} + \sum_{c=1}^C \sum_{m=1}^M \text{Al}_{c,m} + \sum_{c=1}^C \sum_{m'=1}^{M'} \text{Al}_{c,m'} + \sum_{m=1}^M \sum_{r=1}^R \text{Al}_{m,r} + \sum_{m'=1}^{M'} \sum_{r=1}^R \text{Al}_{m',r} + \sum_{r=1}^R \sum_{d=1}^D \text{Al}_{r,d} + \sum_{r=1}^R \sum_{e=1}^E \text{Al}_{r,e} \right) \quad (1-5)$$

$$Z_{1-6} = \sum_{v=1}^V \sum_{f=1}^F \sum_{p=1}^P \sum_{c=1}^C \sum_{t=1}^T \text{Pc}_{p,f} \times \text{US}_{v,f,c,p,t} + \sum_{v=1}^V \sum_{r=1}^R \sum_{e=1}^E \sum_{t=1}^T \text{Pr}_r \times \text{US}_{v,r,e,t} \quad (1-6)$$

$$Z_{1-7} = \text{FPC} \times \left( \sum_{f=1}^F \sum_{s=1}^S \text{Al}_{s,f} + \sum_{f=1}^F \sum_{s'=1}^{S'} \text{Al}_{s',f} \right) + \text{FPR} \times \left( \sum_{r=1}^R \sum_{m=1}^M \text{Al}_{m,r} + \sum_{r=1}^R \sum_{m'=1}^{M'} \text{Al}_{m',r} \right) \quad (1-7)$$

$$Z_{1-8} = \text{lcw} \times \left( \sum_{b=1}^B \sum_{l=1}^L \sum_{t=1}^T \text{Fl}_{b,l,t} + \sum_{s=1}^S \sum_{l=1}^L \sum_{t=1}^T \text{Fl}_{l,s,t} + \sum_{l=1}^L \sum_{s'=1}^{S'} \sum_{t=1}^T \text{Fl}_{l,s',t} + \sum_{s=1}^S \sum_{f=1}^F \sum_{t=1}^T \text{Fl}_{s,f,t} + \sum_{s'=1}^{S'} \sum_{f=1}^F \sum_{t=1}^T \text{Fl}_{s',f,t} \right) \quad (1-8)$$

$$\begin{aligned} \text{Min}Z_2 = & \sum_{v=1}^V \sum_{b=1}^B \sum_{l=1}^L \sum_{t=1}^T \text{VV}_{v,b,l,t} \times \text{Co}_v \times \text{Dis}_{b,l} + \sum_{v=1}^V \sum_{l=1}^L \sum_{s=1}^S \sum_{t=1}^T \text{VV}_{v,l,s,t} \times \text{Co}_v \times \text{Dis}_{l,s} + \\ & \sum_{v=1}^V \sum_{l=1}^L \sum_{s'=1}^{S'} \sum_{t=1}^T \text{VV}_{v,l,s',t} \times \text{Co}_v \times \text{Dis}_{l,s'} + \sum_{v=1}^V \sum_{f=1}^F \sum_{s=1}^S \sum_{t=1}^T \text{VV}_{v,s,f,t} \times \text{Co}_v \times \text{Dis}_{s,f} + \\ & \sum_{v=1}^V \sum_{f=1}^F \sum_{s'=1}^{S'} \sum_{t=1}^T \text{VV}_{v,s',f,t} \times \text{Co}_v \times \text{Dis}_{s',f} + \sum_{v=1}^V \sum_{f=1}^F \sum_{c=1}^C \sum_{t=1}^T \text{VV}_{v,f,c,t} \times \text{Co}_v \times \text{Dis}_{f,c} + \\ & \sum_{v=1}^V \sum_{m=1}^M \sum_{c=1}^C \sum_{t=1}^T \text{VV}_{v,c,m,t} \times \text{Co}_v \times \text{Dis}_{c,m} + \sum_{v=1}^V \sum_{m'=1}^{M'} \sum_{c=1}^C \sum_{t=1}^T \text{VV}_{v,c,m',t} \times \text{Co}_v \times \text{Dis}_{c,m'} + \\ & \sum_{v=1}^V \sum_{m=1}^M \sum_{r=1}^R \sum_{t=1}^T \text{VV}_{v,m,r,t} \times \text{Co}_v \times \text{Dis}_{m,r} + \sum_{v=1}^V \sum_{m'=1}^{M'} \sum_{r=1}^R \sum_{t=1}^T \text{VV}_{v,m',r,t} \times \text{Co}_v \times \text{Dis}_{m',r} + \\ & \sum_{v=1}^V \sum_{e=1}^E \sum_{r=1}^R \sum_{t=1}^T \text{VV}_{v,r,e,t} \times \text{Co}_v \times \text{Dis}_{r,e} + \sum_{v=1}^V \sum_{d=1}^D \sum_{r=1}^R \sum_{t=1}^T \text{VV}_{v,r,d,t} \times \text{Co}_v \times \text{Dis}_{r,d} \end{aligned} \quad (2)$$

$$\text{Min}Z_3 = \sum_{t=1}^T \sum_{b=1}^B \text{Conb} \times \text{HA}_{b,t} + \sum_{t=1}^T \sum_{b=1}^B \text{Wdas} \times \text{HD}_{b,t} \quad (3)$$

$$\text{Max}Z_4 = \sum_{s'=1}^{S'} (\text{ss}_{s'} \times \text{jo}_{s'}) + \sum_{m'=1}^{M'} (\text{sm}_{m'} \times \text{jo}_{m'}) \quad (4)$$

In this research, different aspects of sustainability (economic, environmental, and social) have been considered using four objective functions. The first objective function (1) minimizes total costs. The representation of this objective function using expressions (1-1) to (1-8) is as follows: Expression (1-1) shows the cost of creating new centers that include silos and waste collection centers. Expression (1-2) calculates the cost of ground or rail transportation between different levels of the supply chain. Expression (1-3) calculates the fixed cost of transportation in the entire supply chain (the fixed cost of transportation includes costs such as registering drivers and registering vehicle specifications. Expression (1-4) shows the total storage costs, including the cost of wheat storage in silos, the cost of flour storage in flour factories, and the cost of bread waste storage in waste collection centers and recovery

centers. Expression (1-5) shows the fixed cost of maintenance (which includes costs such as the fixed cost of detoxification of storage places). Expression (1-6) shows the cost of producing wheat flour and recovering products (fertilizer) from bread waste. Expression (1-7) shows the fixed cost of production in flour factories and recovery centers. Expression (1-8) expresses the cost of wheat and flour lost due to transportation at different levels of the supply chain. The second objective function (2) is designed to reduce environmental pollution (the amount of carbon dioxide emitted by vehicles used among different levels of the supply chain). The third objective function (3) minimizes the loss of wheat during harvesting by combine and sickle machines. The fourth objective function (4) maximizes the employment opportunity created by creating new centers.

### Constraints

Following is a definition of the model's constraints:

$$Bw_{b,t} \times wg_{b,t} \leq HA_{b,t} \quad \forall b, t \quad (5)$$

$$Bd_{b,t} \times wd_{b,t} \leq HD_{b,t} \quad \forall b, t \quad (6)$$

Constraint (5) states that the amount of wheat that can be harvested by water method is relevant to the amount of wheat cultivated in farm b and the coefficient of that farm, which is different according to the soil type and the amount of sunlight. Restriction (6) is similar to restriction (5), but the difference is that this restriction is written for dry wheat.

$$\sum_{v=1}^V \sum_{t=1}^T \sum_{i=1}^I \sum_{s=1}^S US_{v,i,s,t} + \sum_{v=1}^V \sum_{t=1}^T \sum_{i=1}^I \sum_{s'=1}^{S'} US_{v,i,s',t} \leq Cap_{esf} \quad (7)$$

$$\sum_{v=1}^V \sum_{l=1}^L US_{v,b,l,t} \leq (HA_{b,t} + HD_{b,t}) \quad \forall b, t \quad (8)$$

$$\sum_{v=1}^V \sum_{b=1}^B US_{v,b,l,t} = \sum_{v=1}^V \sum_{s=1}^S US_{v,l,s,t} + \sum_{v=1}^V \sum_{s'=1}^{S'} US_{v,l,s',t} \quad \forall l, t \quad (9)$$

$$\sum_{v=1}^V \sum_{b=1}^B US_{v,b,l,t} \leq Cap_{l,t} \quad \forall l, t \quad (10)$$

$$\sum_{v=1}^V \sum_{l=1}^L US_{v,l,s,t} + \sum_{v=1}^V \sum_{i=1}^I US_{v,i,s,t} \leq Cap_{s,t} \quad \forall s, t \quad (11)$$

$$\sum_{v=1}^V \sum_{l=1}^L US_{v,l,s',t} + \sum_{v=1}^V \sum_{i=1}^I US_{v,i,s',t} \leq Cap_{s',t} \times SS_{s'} \quad \forall s', t \quad (12)$$

$$\sum_{v=1}^V \sum_{s=1}^S US_{v,s,f,t} + \sum_{v=1}^V \sum_{s'=1}^{S'} US_{v,s',f,t} \leq Cap_{f,t} \quad \forall f, t \quad (13)$$

$$\sum_{v=1}^V \sum_{f=1}^F US_{v,s,f,t} \leq Cap_{s,t} \quad \forall s, t \quad (14)$$

$$\sum_{v=1}^V \sum_{f=1}^F US_{v,s',f,t} \leq Cap_{s',t} \times SS_{s'} \quad \forall s', t \quad (15)$$

$$\sum_{v=1}^V \sum_{c=1}^C US_{v,c,m,t} \leq Cap_{m,t} \quad \forall m, t \quad (16)$$

$$\sum_{v=1}^V \sum_{c=1}^C US_{v,c,m',t} \leq Cap_{m',t} \times SS_{m'} \quad \forall m', t \quad (17)$$

$$\begin{aligned}
\sum_{v=1}^V \sum_{m=1}^M US_{v,m,r,t} + \sum_{v=1}^V \sum_{m'=1}^{M'} US_{v,m',r,t} &\leq \text{Cap}_{r,t} && \forall r, t && \infty \\
\sum_{v=1}^V \sum_{r=1}^R US_{v,r,d,t} &\leq \text{Cap}_{d,t} && \forall d, t && \infty \\
\sum_{v=1}^V \sum_{l=1}^L \sum_{s=1}^S US_{v,l,s,t} + \sum_{v=1}^V \sum_{i=1}^I \sum_{s=1}^S US_{v,i,s,t} + \sum_{v=1}^V \sum_{l=1}^L \sum_{s'=1}^{S'} US_{v,l,s',t} + \sum_{v=1}^V \sum_{i=1}^I \sum_{s'=1}^{S'} US_{v,i,s',t} &\geq \text{need}_t && \forall t && \infty \\
\sum_{v=1}^V USw_{v,f,t} &\leq \left( \sum_{v=1}^V \sum_{s=1}^S US_{v,s,f,t} + \sum_{v=1}^V \sum_{s'=1}^{S'} US_{v,s',f,t} \right) \times \sum_{p=1}^P (q_p \times l_p) && \forall f, t && \infty
\end{aligned}$$

Constraint (7) states that the amount of wheat sent by foreign suppliers is not more than the maximum import capacity to this province. Constraint (8) states that the amount of wheat delivered from a farm to the shopping center is less than the amount that can be harvested from that farm. Constraint (9) states that all wheat delivered to centers must be delivered to silos. Constraints (10) to (19) state that the amount of product (wheat, flour, and waste) transported between the levels of the chain should be according to the capacity of different centers. Constraint (20) shows the province's total need for domestically grown and imported wheat. The amount of imported wheat and wheat harvested from farms should meet the province's needs. Constraint (21) shows the amount of transfer of bran, straw, etc., from the flour factory to the animal feed center, which is calculated according to the amount of wheat imported to the factory and the percentage of wheat that is not needed and is not made into flour.

$$\sum_{v=1}^V \sum_{i=1}^I US_{v,i,s,t} + \sum_{v=1}^V \sum_{l=1}^L US_{v,l,s,t} + \text{Inv}_{s,t-1} = \text{Inv}_{s,t} + \sum_{v=1}^V \sum_{f=1}^F US_{v,s,f,t} \quad \forall s, t > 1 \quad (22)$$

$$\sum_{v=1}^V \sum_{i=1}^I US_{v,i,s',t} + \sum_{v=1}^V \sum_{l=1}^L US_{v,l,s',t} + \text{Inv}_{s',t-1} = \text{Inv}_{s',t} + \sum_{v=1}^V \sum_{f=1}^F US_{v,s',f,t} \quad \forall s', t > 1 \quad (23)$$

$$\text{Inv}_{s,t} \geq \text{ssa} \quad \forall s, t \quad (24)$$

$$\text{Inv}_{s',t} \geq \text{ssa} \times \text{SS}_{s'} \quad \forall s', t \quad (25)$$

$$\sum_{v=1}^V \sum_{s=1}^S US_{v,s,f,t} + \sum_{v=1}^V \sum_{s'=1}^{S'} US_{v,s',f,t} - \sum_{v=1}^V \sum_{c=1}^C \sum_{p=1}^P US_{v,f,c,p,t} - \sum_{v=1}^V USw_{v,f,t} + \text{Inv}_{f,t-1} = \text{Inv}_{f,t} \quad \forall f, t \quad (26)$$

$$\left( \sum_{v=1}^V \sum_{s=1}^S US_{v,s,f,t} + \sum_{v=1}^V \sum_{s'=1}^{S'} US_{v,s',f,t} \right) \times b_p \times l_p = \text{Pro}_{f,p,t} \quad \forall f, p, t \quad (27)$$

$$\text{Pro}_{f,p,t} \geq \sum_{v=1}^V \sum_{c=1}^C US_{v,f,c,p,t} \quad \forall f, p, t \quad (28)$$

$$\sum_{v=1}^V \sum_{c=1}^C US_{v,c,m,t} - \sum_{v=1}^V \sum_{r=1}^R US_{v,m,r,t} - \sum_{v=1}^V USw_{v,m,t} + \text{Inv}_{m,t-1} = \text{Inv}_{m,t} \quad \forall m, t \quad (29)$$

$$\sum_{v=1}^V \sum_{c=1}^C US_{v,c,m',t} - \sum_{v=1}^V \sum_{r=1}^R US_{v,m',r,t} - \sum_{v=1}^V USw_{v,m',t} + \text{Inv}_{m',t-1} = \text{Inv}_{m',t} \quad \forall m', t \quad (30)$$

$$\sum_{v=1}^V \sum_{f=1}^F \sum_{p=1}^P US_{v,f,c,p,t} \times \text{wt} \times \text{pb}_p = \sum_{v=1}^V \sum_{m=1}^M US_{v,c,m,t} + \sum_{v=1}^V \sum_{m'=1}^{M'} US_{v,c,m',t} \quad \forall c, t \quad (31)$$

$$\sum_{v=1}^V \sum_{m=1}^M US_{v,m,r,t} + \sum_{v=1}^V \sum_{m'=1}^{M'} US_{v,m',r,t} - \sum_{v=1}^V \sum_{d=1}^D US_{v,r,d,t} - \sum_{v=1}^V \sum_{e=1}^E US_{v,r,e,t} + \text{Inv}_{r,t-1} = \text{Inv}_{r,t} \quad \forall r, t \quad (32)$$

$$\sum_{v=1}^V \sum_{c=1}^C US_{v,c,m,t} \times m = \sum_{v=1}^V USw_{v,m,t} \quad \forall m, t \quad (33)$$

$$\sum_{v=1}^V \sum_{c=1}^C US_{v,c,m',t} \times m = \sum_{v=1}^V USw_{v,m',t} \quad \forall m', t \quad (34)$$

$$\sum_{v=1}^V \sum_{c=1}^C US_{v,c,m,t} \times (1-m) = \sum_{v=1}^V \sum_{r=1}^R US_{v,m,r,t} \quad \forall m, t \quad (35)$$

$$\sum_{v=1}^V \sum_{c=1}^C US_{v,c,m',t} \times (1-m) = \sum_{v=1}^V \sum_{r=1}^R US_{v,m',r,t} \quad \forall m', t \quad (36)$$

$$\left( \sum_{v=1}^V \sum_{m=1}^M US_{v,m,r,t} + \sum_{v=1}^V \sum_{m'=1}^{M'} US_{v,m',r,t} \right) \times w = \sum_{v=1}^V \sum_{e=1}^E US_{v,r,e,t} \quad \forall r, t \quad (37)$$

$$\left( \sum_{v=1}^V \sum_{m=1}^M US_{v,m,r,t} + \sum_{v=1}^V \sum_{m'=1}^{M'} US_{v,m',r,t} \right) \times (1-w) = \sum_{v=1}^V \sum_{d=1}^D US_{v,r,d,t} \quad \forall r, t \quad (38)$$

$$\sum_{v=1}^V \sum_{r=1}^R US_{v,r,d,t} + Inv_{d,t-1} = Inv_{d,t} \quad \forall d, t \quad (39)$$

Constraints (22) and (23) show the flow balance in existing silos and new silos, respectively. Considering that the amount of wheat storage in silos should not be less than a provincial limit, constraints (24) and (25) show strategic storage in existing silos and new silos. Constraints (26), (29), (30), (32), and (39) show the balance of inventory flow in flour mills, existing and new waste collection centers, recovery centers, and disposal centers, respectively. Constraint (27) illustrates how much of various types of flour are produced in flour factories, and constraint (28) expresses the balance between the amount of wheat transported to flour factories and the amount of flour produced there. Constraint (31) calculates the amount of waste that returns to the cycle, and constraints (33) and (34) show the amount of food produced for animals. Constraints (35) and (36) show the amount of waste used to make fertilizer. Constraint (37) shows the amount of fertilizer produced. Constraint (38) illustrates the amount of unrecoverable waste sent to disposal centers.

$$\sum_{s=1}^S \sum_{v=1}^V US_{v,s,f,t} + \sum_{s'=1}^{S'} \sum_{v=1}^V US_{v,s',f,t} \geq Df_{f,t} \quad \forall f, t \quad (40)$$

$$\sum_{v=1}^V \sum_{f=1}^F US_{v,f,c,p,t} \geq Dp_{p,c,t} \quad \forall p, c, t \quad (41)$$

$$\sum_{v=1}^V \sum_{r=1}^R US_{v,r,e,t} \geq Do_{e,t} \quad \forall e, t \quad (42)$$

Constraint (40) shows the demand of flour mills from silos to receive wheat. Constraints (41) and (42) show the amount of demand for products produced from wheat and the amount of customer demand for recovered products, respectively.

$$\sum_{s'=1}^{S'} ss_{s'} \leq 1 \quad (43)$$

$$\sum_{m'=1}^{M'} sm_{m'} \leq 1 \quad (44)$$

$$\sum_{l=1}^L Al_{l,s'} \leq U \times SS_{s'} \quad \forall s' \quad (45)$$

$$\sum_{i=1}^I Al_{i,s'} \leq U \times SS_{s'} \quad \forall s' \quad (46)$$

$$\sum_{i=1}^I Al_{s',f} \leq U \times SS_{s'} \quad \forall s' \quad (47)$$

$$\sum_{c=1}^C Al_{c,m'} \leq U \times Sm_{m'} \quad \forall m' \quad (48)$$

$$\sum_{r=1}^R Al_{m',r} \leq U \times Sm_{m'} \quad \forall m' \quad (49)$$

Constraints (43) and (44) state that only one facility can be placed in the potential location. If the potential center is opened, constraints (45) to (49) determine the transport flow.

$$\sum_{v=1}^V \sum_{t=1}^T US_{v,l,s,t} \leq U \times AI_{l,s} \quad \forall l, s \quad (50)$$

$$\sum_{v=1}^V \sum_{t=1}^T US_{v,l,s',t} \leq U \times AI_{l,s'} \quad \forall l, s' \quad (51)$$

$$\sum_{v=1}^V \sum_{t=1}^T US_{v,s,f,t} \leq U \times AI_{s,f} \quad \forall s, f \quad (52)$$

$$\sum_{v=1}^V \sum_{t=1}^T US_{v,s',f,t} \leq U \times AI_{s',f} \quad \forall s', f \quad (53)$$

$$\sum_{v=1}^V \sum_{t=1}^T \sum_{p=1}^P US_{v,f,c,p,t} \leq U \times AI_{f,c} \quad \forall f, c \quad (54)$$

$$\sum_{v=1}^V \sum_{t=1}^T US_{v,c,m,t} \leq U \times AI_{c,m} \quad \forall c, m \quad (55)$$

$$\sum_{v=1}^V \sum_{t=1}^T US_{v,c,m',t} \leq U \times AI_{c,m'} \quad \forall c, m' \quad (56)$$

$$\sum_{v=1}^V \sum_{t=1}^T US_{v,m,r,t} \leq U \times AI_{m,r} \quad \forall m, r \quad (57)$$

$$\sum_{v=1}^V \sum_{t=1}^T US_{v,m',r,t} \leq U \times AI_{m',r} \quad \forall m', r \quad (58)$$

$$\sum_{v=1}^V \sum_{t=1}^T US_{v,r,d,t} \leq U \times AI_{r,d} \quad \forall r, d \quad (59)$$

$$\sum_{v=1}^V \sum_{t=1}^T US_{v,r,e,t} \leq U \times AI_{r,e} \quad \forall r, e \quad (60)$$

$$\sum_{v=1}^V \sum_{t=1}^T US_{v,i,s,t} \leq U \times AI_{i,s} \quad \forall i, s \quad (61)$$

$$\sum_{v=1}^V \sum_{t=1}^T US_{v,i,s',t} \leq U \times AI_{i,s'} \quad \forall i, s' \quad (62)$$

Constraints (50) to (62) show the allocation of different centers.

$$Fl_{b,l,t} = \sum_{v=1}^V (lc_v \times US_{v,b,l,t} \times Dis_{b,l}) \quad \forall b, l, t \quad (63)$$

$$Fl_{l,s,t} = \sum_{v=1}^V (lc_v \times US_{v,l,s,t} \times Dis_{l,s}) \quad \forall l, s, t \quad (64)$$

$$Fl_{l,s',t} = \sum_{v=1}^V (lc_v \times US_{v,l,s',t} \times Dis_{l,s'}) \quad \forall l, s', t \quad (65)$$

$$Fl_{s,f,t} = \sum_{v=1}^V (lc_v \times US_{v,s,f,t} \times Dis_{s,f}) \quad \forall s, f, t \quad (66)$$

$$Fl_{s',f,t} = \sum_{v=1}^V (lc_v \times US_{v,s',f,t} \times Dis_{s',f}) \quad \forall s', f, t \quad (67)$$

Constraints (63) to (67) show the wheat loss due to transportation.

$$US_{v,b,l,t} \leq Cap_v \times VV_{v,b,l,t} \quad \forall v, b, l, t \quad (68)$$

$$US_{v,l,s,t} \leq Cap_v \times VV_{v,l,s,t} \quad \forall v, l, s, t \quad (69)$$

$$US_{v,l,s',t} \leq Cap_v \times VV_{v,l,s',t} \quad \forall v, l, s', t \quad (70)$$

$$US_{v,s,f,t} \leq Cap_v \times VV_{v,s,f,t} \quad \forall v, s, f, t \quad (71)$$

$$US_{v,s',f,t} \leq Cap_v \times VV_{v,s',f,t} \quad \forall v, s', f, t \quad (72)$$

$$\sum_{p=1}^P US_{v,f,c,p,t} \leq Cap_v \times VV_{v,f,c,t} \quad \forall v, f, c, t \quad (73)$$

$$US_{v,c,m,t} \leq Cap_v \times VV_{v,c,m,t} \quad \forall v, c, m, t \quad (74)$$

$$US_{v,c,m',t} \leq Cap_v \times VV_{v,c,m',t} \quad \forall v, c, m', t \quad (75)$$

$$US_{v,m,r,t} \leq Cap_v \times VV_{v,m,r,t} \quad \forall v, m, r, t \quad (76)$$

$$US_{v,m',r,t} \leq Cap_v \times VV_{v,m',r,t} \quad \forall v, m', r, t \quad (77)$$

$$US_{v,r,e,t} \leq Cap_v \times VV_{v,r,e,t} \quad \forall v, r, e, t \quad (78)$$

$$US_{v,r,d,t} \leq Cap_v \times VV_{v,r,d,t} \quad \forall v, r, d, t \quad (79)$$

$$USw_{v,f,t} \leq Cap_v \times VV_{v,f,t} \quad \forall v, f, t \quad (80)$$

$$USw_{v,m,t} \leq Cap_v \times VV_{v,m,t} \quad \forall v, m, t \quad (81)$$

$$US_{v,m',t} \leq Cap_v \times VV_{v,m',t} \quad \forall v, m', t \quad (82)$$

Constraints (68) to (82) state that the amount of product transported between different levels of the supply chain should be determined according to the capacity of the vehicles used.

$$SS_{s'}, Sm_{m'}, Al_{b,l}, Al_{l,s}, Al_{l,s'}, Al_{s,f}, Al_{s',f}, Al_{f,c}, Al_{c,m}, Al_{c,m'}, Al_{m,r}, Al_{m',r}, Al_{r,d}, Al_{r,e}, Al_{l,s}, Al_{l,s'} \in \{0,1\} \quad (83)$$

$$US_{v,b,l,t}, US_{v,l,s,t}, US_{v,l,s',t}, US_{v,i,s,t}, US_{v,i,s',t}, US_{v,s,f,t}, US_{v,s',f,t}, US_{v,f,c,p,t}, USw_{v,f,t}, US_{v,c,m,t}, US_{v,c,m',t}, USw_{v,m,t}, US_{v,m',t}, US_{v,m,r,t}, US_{v,m',r,t}, US_{v,r,d,t}, pro_{f,p,t}, HA_b, HD_b \geq 0 \quad (84)$$

$$Inv_{l,t}, Inv_{s,t}, Inv_{s',t}, Inv_{m,t}, Inv_{m',t}, Inv_{f,t}, Inv_{r,t}, Fl_{b,l,t}, Fl_{l,s,t}, Fl_{l,s',t}, Fl_{s,f,t}, Fl_{s',f,t}, VV_{v,l,s,t}, VV_{v,l,s',t}, VV_{v,s,f,t}, VV_{v,s',f,t}, VV_{v,f,c,t}, VV_{v,f,t}, VV_{v,c,m,t}, VV_{v,m,r,t}, VV_{v,m',r,t}, VV_{v,l,s,t}, VV_{v,l,s',t}, VV_{v,m,t}, VV_{v,m',t}, VV_{v,r,e,t} \in Z^+ \quad (85)$$

Constraints (83), (84), and (85) represent binary variables, continuous variables, and integer variables of the model, respectively.

#### 4. Solution method

Various methods have been presented to solve multi-objective problems, including the weighted sum method, epsilon constraint, Augmented Epsilon Constraint, Goal Programming, etc. In addition to the mentioned methods, meta-heuristic methods have also been developed to solve complex multi-objective problems, among which Genetic Algorithm, Ant Colony Algorithm, Simulated Annealing, etc. methods can be mentioned (Marler & Arora, 2004).

In the present study, the  $\epsilon$ -constraint method is employed to address the multi-objective optimization problem. This technique is widely recognized for its effectiveness in transforming a multi-objective problem into a series of single-objective subproblems. In this approach, one objective is optimized, while the remaining objectives are incorporated as constraints with specified upper or lower bounds ( $\epsilon$  values). By systematically varying these bounds, a diverse set of Pareto-optimal solutions can be obtained, enabling decision-makers to evaluate trade-offs among conflicting objectives (Mavrotas, 2009).

This method has been widely used in sustainability-related studies. For instance, Hejazi and Khorshidvand (2024) applied it to generate Pareto fronts and introduced a new scoring approach to identify optimal trade-offs in

designing a sustainable closed-loop supply chain (CLSC). Their model incorporates socio-economic, environmental, and economic objectives while addressing demand uncertainties.

#### Pareto optimality

Since multi-objective optimization problems generally have incompatible objectives, it is usually impossible to achieve a solution that can optimize all the objectives of the problem simultaneously. In multi-objective problems, another concept of optimal solution is expressed, known as Pareto optimality. To explain Pareto optimality, it is first necessary to explain the concept of dominance. In multi-objective optimization problems (of the minimization type), the solution  $x$  overcomes the solution  $y$  ( $x < y$ ) if:

$$F_i(X) \leq F_i(Y) \quad \text{For all } i \in \{1, 2, 3, \dots, m\} \quad (4-1)$$

$$F_i(X) < F_i(Y) \quad \text{For at least one } i \in \{1, 2, 3, \dots, m\} \quad (4-2)$$

In the above expressions,  $m$  is the number of objective functions, and finding a set of Pareto optimal solutions to a multi-objective optimization problem is the aim of the solving process because each of the solutions in this set is preferable to the others in at least one of the objectives (Zhang & Reimann, 2014).

#### Epsilon-constraint method

A multi-objective problem generally takes the following form.

$$\begin{cases} \text{Min } (f_1(x), f_2(x), \dots, f_n(x)) \\ x \in X \end{cases} \quad (4-3)$$

Suppose the first objective is taken as the primary objective, and the upper bound of epsilon is the limit for other objectives, which are applied as constraints on the problem. The following single-objective model is created using the epsilon-constraint method; the first objective is regarded as the primary objective, and the objectives from the second to the  $n$ th are constrained to the maximum epsilon value ( $e_i$ ).

$$\begin{cases} \text{Min } f_1(x) \\ f_i(x) \leq e_i \quad i=2, 3, \dots, n \\ x \in X \end{cases} \quad (4-4)$$

#### Enhanced epsilon-constraint method

The enhanced epsilon-constraint method is developed to solve some of the conventional epsilon constraint's weaknesses and solve problems with more than two objective functions. In this method, the unequal constraint of the epsilon-constraint method is converted into an equal constraint by adding a positive slack variable, and the weighted sum of the slack variables to the objective function strengthens the original objective function (Mavrotas, 2007). The steps of the method are:

- (1) Forming the payoff table: In this step, the Lexicographic optimization method generates Pareto solutions. This method is used in situations where the indicators' significance for the decision maker is not the same, and its purpose is to rank the research options.
- (2) Calculation of the lower limit of the objective function: this limit is determined using the balance table.
- (3) Determining the range of the  $k$ th objective function ( $r_k$ ):

$$r_k = f_k^{\max} - f_k^{\min}, \quad k=2, \dots, p \quad (4-6)$$

The values of  $f_k^{\max}$  and  $f_k^{\min}$  are respectively the highest and lowest values of each objective function in the balance table.

- (4) Dividing the range of each objective function into equal distance  $g_k$  and determining the values of  $e_k$ :

$$e_k = f_k^{\min} + \frac{r_k \times i_k}{g_k}, \quad i_k = 1, 2, \dots, g_k \quad (4-7)$$

- (5) Transforming the multi-objective model into a single-objective model based on the enhanced epsilon-constraint method.

$$\max f_1(x) + \text{eps} \left( \frac{s_2}{r_2} + \frac{s_3}{r_3} + \dots + \frac{s_p}{r_p} \right)$$

*S. T:*

$$\begin{aligned} f_k(x) - s_k &= e_k, & k=2,3,\dots,p \\ x &\in S, s_k \in \mathbb{R}^+ \end{aligned} \quad (4-8)$$

In equation (4-8),  $x$  is the vector of decision variables,  $r_k$  is the range of the objective function (i.e., the minimum and maximum value of the objective function),  $s_k$  represents the slack variable, and  $e_k$  is the value on the right side of the limitation related to the objective function, and  $S$  is the problem space. Also,  $\text{eps}$  is considered a number between  $10^{-3}$  and  $10^{-6}$ .

## 5. Case Study

Isfahan is one of Iran's dry provinces, where wheat production is very low compared to imports due to challenging weather conditions and a lack of water. Therefore, focusing on the categories of loss and wastage of wheat and making efforts to reduce them throughout the supply chain can significantly help decrease the imports of this product. The current study is based on the information gathered from the wheat supply chain network of Isfahan province, which part of this network is shown in Figure 2. This information is from the period of July 2020 to December 2021 and from various sources such as Isfahan Governorate, Isfahan General Department of Grain and Commercial Services, Agricultural Jihad Organization, Waste Management and Waste Organization, Abadan Transport Department, Baharestan Flour Factory and General Department Environmental Protection of Isfahan province has been collected, the relevant information is given in Table 3. To reduce the complexity of the problem, wheat cultivation fields and shopping centers in Isfahan province have been considered regionally. Additionally, there are approximately 4,800 bakeries in this province producing Tufton, Sangak, and Fantasy bread. To simplify calculations, we have considered three main distribution centers for these three types of flour.

Regarding the wheat supply chain network of Isfahan province, it seems necessary to mention the following points:

- Wheat cultivation in the fields of Isfahan province is carried out in two ways: rainfed and irrigated. Harvesting in irrigated areas is usually done with a combined harvester, while in dry farming areas, it uses a sickle. Consequently, 92.5% of wheat harvesting in the province is accomplished with combined harvesters, while the remaining 7.5% is done manually. The loss of wheat during harvesting with old combine harvesters was 5.7%, which decreased to 1.67% with new models. Additionally, the wastage of wheat during harvesting with a sickle is 7%.
- In this research, three types of flour have been considered as the main wheat products: Khabazi flour, Sangak flour, and Se-Sefr flour (Super Fine Flour), which serve as the primary ingredients for Tufton bread, Sangak bread, and Fantasy bread, respectively. According to the obtained information, the fixed cost of flour production is 10 million Tomans per month, which includes costs such as equipment depreciation. The remaining costs and corresponding conversion factors are provided in Table 4. For example, based on this table, each kilogram of wheat produces 0.86 kg of Khabazi flour, and each kilogram of Khabazi flour generates 1.26 kg of Tufton bread. This province's amount of bread waste is 5%, and the cost of converting each kilogram of bread waste into fertilizer is 11,000 Tomans. The amount of wheat wastage per ton-kilometer of transportation is 0.0002 tons, and the cost of wheat wastage is 6,500 Tomans per kilogram of wheat.
- The capacity of vehicles varies, with trucks rated at 10 tons, trailers at 25 tons, and trains at 1,200 tons. Each vehicle has its specific application: wheat is imported by train, wheat is transported from fields to silos, and waste is transported by trucks to collection, recovery, and disposal centers, as well as to animal feed centers. Transportation from shopping centers to silos and from silos to flour factories is carried out by trailers. In addition, each vehicle produces an average of 0.069 kg of carbon dioxide per kilometer traveled. The storage

capacity in shopping centers varies across regions depending on local cultivation. The maximum import capacity of the province is 500,000 tons. The demand for wheat for each factory varies according to its flour production capacity. Maintenance costs, transportation costs, shopping center capacities (regionally), the costs of establishing new facilities and related job opportunities, and the capacities of the province's flour factories are presented in Tables 5 to 9, respectively. All measurement units are tons, kilometers, and hectares, and all cost units are in Tomans.

**Table 3.** Information related to the wheat supply chain network of Isfahan province

3	Number of external suppliers (I)
24	Number of wheat fields (B)
24	Number of guaranteed shopping centers (L)
2	Number of available silos (S)
1	Number of potential silos to build (S')
20	Number of flour factories (F)
3	Number of demand centers (C)
3	Number of available waste collection centers (M)
1	Number of potential waste collection centers for construction (M')
1	Number of disposal centers (D)
1	Number of recovery centers (R)
3	Horizon planning (in years) (T)

**Table 4.** Information about the production cost of each kilo of flour and the corresponding conversion coefficient

Flour type	Production cost per kilo (toman)	Conversion coefficient wheat to flour	Conversion coefficient of flour to bread
Khabazi	1950	0.86	1.26
Sangak	2000	0.86	1.33
Se-Sefr	2100	0.79	1.22

**Table 5.** Holding costs ( $\frac{\text{tomans}}{\text{ton*month}}$ )

shopping center	10000	flour factory	50000	Recovery centers	30000
Silos	300000	Waste collection centers	24000	Fix cost	50000

**Table 6.** Transportation costs ( $\frac{\text{tomans}}{\text{ton*kilometer}}$ )

From field to shopping center	400	From demand center to collection center	5000
From shopping center to silo	9500	From collection center to recovery center	10000
From import to silo	165	From recovery center to disposal center	20000
From silo to flour factory	12000	From recovery center to customer	10000
From flour factory to demand center	7000	From collection center to animal feed	8000
From factory to animal feed	7000	Fixed cost per month	1000000

**Table 7.** Capacity of shopping centers (tons)

shopping center	Capacity	shopping center	Capacity	shopping center	Capacity	shopping center	Capacity
Aran and Bidgol	1500	Chadegan	9000	Shahinshahr	9000	Golpayegan	7000
Ardestan	4500	Khomeinishahr	4000	Shahreza	6500	Lenjan	1200
Isfahan	37000	Khansar	2000	Fereydan	8500	Mobarakeh	7000
Borkhar	14000	Khur and Biabanak	1000	Fereydunshahr	5500	Naein	1300
Boein Miandasht	5000	Dehaghan	6000	Falavarjan	5000	Najafabad	2000
Tiran and Karvan	5000	Semirom	4000	Kashan	2500	Natanz	1500

**Table 8.** The cost of establishing potential centers and job opportunities created

Potential center for the establishment	Establishment cost	Job opportunity
Silo	200 milliard	22 people
Waste collection center	28 million	6 people

**Table 9.** Capacity of flour factories (tons)

Factory	Capacity	Factory	Capacity	Factory	Capacity	Factory	Capacity	Factory	Capacity
1	7000	5	20000	9	1500	13	53000	17	43000
2	20700	6	20000	10	9800	14	16000	18	104000
3	36000	7	9000	11	11000	15	89000	19	7000
4	36000	8	6000	12	21000	16	103000	20	17000

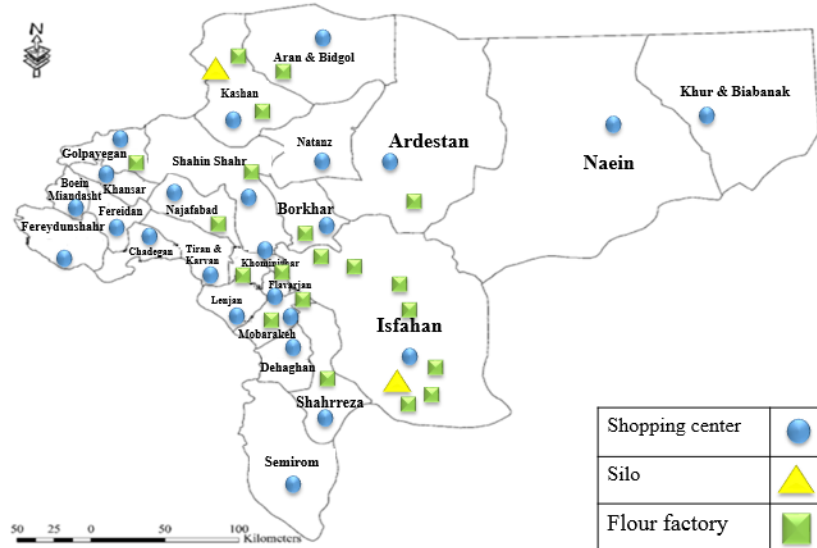


Figure 2. Shopping centers, silos, and factories in Isfahan province

6. Model results

The model presented in the current research is based on a sustainability approach and includes four objective functions: reducing economic costs (the first objective function), minimizing the amount of carbon dioxide produced (the second objective function), decreasing wheat wastage (the third objective function), and increasing job opportunities through the construction of new facilities (the fourth objective function). This model is based on information obtained from the wheat supply chain network of Isfahan Province, as introduced in the previous section. It was implemented in GAMS 28.2.0 software and solved using the CPLEX solver on a computer with Intel i7-2.3 GHz CPU specifications and 4 GB RAM. The problem was solved in 8 hours, 16 minutes, and 48 seconds, resulting in 27 solutions identified as Pareto optimal solutions. Due to the inability to draw a four-dimensional diagram, the Pareto frontier diagram was not created, and these solutions are illustrated in Table 10. It should be noted that the value of  $g_k$  in the Augmented Epsilon Constraint method (in formula 4-7) is assumed to be equal to 140, and the value of  $i_k$  is considered to be equal to  $g_k$ . Paying attention to the obtained Pareto solutions and the stability of the value of the fourth objective function (F4) in all of them, it can be concluded that this function, in its optimality, necessitates the construction of a new silo and a new waste collection center. To validate and solve the proposed model, Different scenarios were examined according to the dimensions of the problem, and the information about six scenarios is given in Table 11. The noteworthy point in this table is the division of problem representations (problem states) into three categories on a small, medium, and large scale to assess the performance of the model presented. Table 11 shows the best amount of objective functions for different scenarios. According to the obtained results, it can be seen that with the increase of different dimensions of the problem, the values of the first, second, and third objective functions, which respectively indicate the amount of the supply chain economic costs, the amount of carbon dioxide emitted and the amount of wheat wastage, have increased. The solving time of the problem also increases as the problem dimension increases, which indicates the complexity of solving the model in real and large dimensions.

Table 10. Pareto optimal solution

No.	The first objective function (* 10 <sup>12</sup> )	The second objective function	The third objective function	The fourth objective function
1	2.60134	573633.96	26508.31	28
2	2.601342	573609.61	26508.31	28
3	2.601344	573574.69	26508.31	28
4	2.601347	573538.98	26508.31	28
5	2.601349	573503.47	26508.31	28
6	2.601352	573467.76	26508.31	28
7	2.601352	572963.32	26508.31	28
8	2.601353	572933.8	26508.31	28
9	2.601356	572898.3	26508.31	28
10	2.601359	572862.39	26508.31	28
11	2.601361	572826.69	26508.31	28

12	2.601364	572791.18	26508.31	28
13	2.601366	572755.67	26508.31	28
14	2.60137	572720.26	26508.31	28
15	2.601375	572684.71	26508.31	28
16	2.60138	572649.11	26465.56	28
17	2.601385	572613.45	26465.56	28
18	2.60139	572577.82	26465.56	28
19	2.601395	572542.27	26465.56	28
20	2.6014	572506.67	26465.56	28
21	2.601404	572471	26465.56	28
22	2.601409	572435.49	26465.56	28
23	2.601415	572399.89	26462.71	28
24	2.601421	572364.22	26439.91	28
25	2.601428	572328.72	26508.31	28
26	2.601435	572293.11	26508.31	28
27	2.601442	572257.44	26453.22	28

**Table 11.** Different instances of the problem and their results

Instance	Size (dimensions) of the problem								The results of the exact solution (GAMS)					
	I	B	L	S	F	C	P	M	F1 (* 10 <sup>11</sup> )	F2 (* 10 <sup>4</sup> )	F3	F4 (person)	Solving time (minutes)	
Small Scale	TP1	1	10	10	1	4	1	1	1	4.701748	7.428421	14420.45	28	2:36:12
	TP2	2	12	12	2	6	2	2	2	8.805105	7.827641	16753.70	28	5:40:36
Medium Scale	TP3	3	16	16	3	12	3	3	3	10.06763	17.33601	21392.58	28	9:13:31
	TP4	4	18	18	4	15	4	4	4	13.7271	19.357036	22582.16	28	12:36:07
Large Scale	TP5	5	22	22	4	20	5	5	5	14.6481	27.90658	25466.935	28	18:12:29
	TP6	6	26	26	5	25	6	6	6	36.4168	56.665763	27684.486	28	21:19:43

## 7. Sensitivity analysis

To conduct a more precise analysis of the waste and loss of wheat at various stages of the supply chain for this product, a sensitivity analysis was performed based on various parameters used in the proposed model in this research, with some of these factors mentioned below:

### a) Wheat wastage during transportation:

Waste due to transportation is observed at various stages of the wheat supply chain. Inaccuracy in handling wheat, the use of outdated transportation means, and the lack of proper coverage during the transportation of the product are among the main factors contributing to wheat wastage. According to standards, if truck and trailer drivers adhere to safety guidelines and ensure that vehicles are fully sealed and insulated, the wastage per ton-kilometer of wheat transported will be 0.00005 tons. However, according to the data obtained in this research, the actual wastage in our country is 0.0002 tons. This wastage can be significantly reduced with proper management and adherence to simple guidelines, as well as by mandating contractors to use specialized grain transport trucks. The sensitivity analysis results regarding the wastage per ton of wheat transported by a vehicle over a unit distance (lcv) can be seen in Table 12. These results, as summarized in Figure 3, indicate that small changes in this coefficient can significantly reduce wastage.

### b) Wheat wastage at harvest time:

Using appropriate methods for harvesting wheat significantly reduces the wastage of this product. As previously mentioned, a large portion of wheat harvesting in Isfahan Province uses combined harvesters. The age of these machines, whether old or new, considerably impacts the level of wheat wastage. It is estimated that the wastage percentage in machines older than 7 years is 5.7%, while in newer machines it is 1.6%. To highlight the importance of this issue and the impact of combined harvester losses in harvesting each ton of wheat (Comb), three scenarios regarding farms in this province have been considered, with the relevant results presented in Table 13.

- **First scenario:** All farms use only old machines.
- **Second scenario:** Old machines are used in 50% of the farms, while new machines are used in the other 50%.
- **Third scenario:** All farms in the province use new machines.

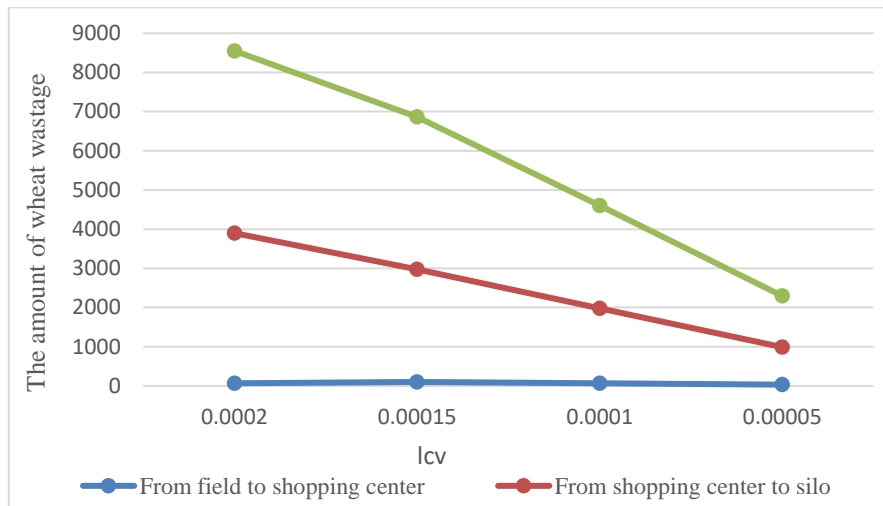
The results indicate that the use of new combine harvesters can significantly reduce wheat waste. Therefore, considering that over 80% of the vehicles used in Isfahan Province are old, replacing old combined harvesters with new ones as much as possible is essential to reducing wheat wastage.

**Table 12.** Comparing the amount of wheat wastage due to transportation according to different wastage coefficients ( $\frac{tons}{year}$ )

Wastage coefficients (lcv)	0.0002	0.00015	0.0001	0.00005
From field to shopping center	133.068	99.85	66.535	31.259
From shopping center to silo	3829.84	2872.1	1915.23	957.312
From silo to flour factory	4651.74	3894.44	2615.78	1307.87
Total	8614.648	6866.39	4597.54	2296.44

**Table 13.** The amount of wheat wastage ( $\frac{tons}{year}$ ) in different scenarios of using the table 14 machine

Scenario	The amount of wheat wastage
1	25603.587
2	16776.025
3	7948.464



**Figure 3.** The effect of the wastage coefficient (lcv) on the amount of wheat wastage due to transportation ( $\frac{tons}{year}$ )

**c) Bread Waste Rate (Wt):**

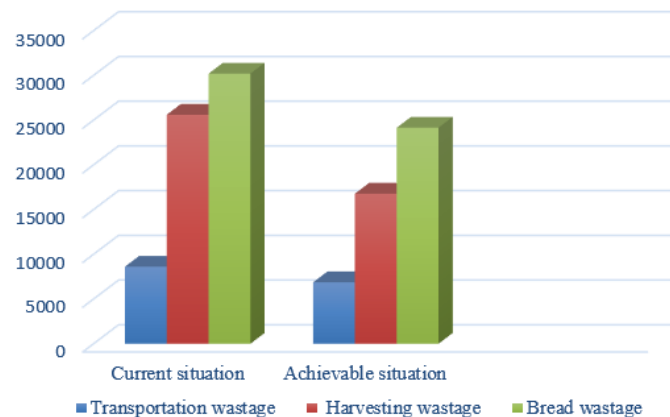
In Isfahan province, bread waste is estimated to be around 5%, which is relatively low compared to larger provinces such as Tehran, where it reaches approximately 30% in some cases. However, reducing even this percentage of waste is essential. To achieve this, greater attention should be given to the quality of flour, the baking process, and the proper storage of bread by consumers. Nevertheless, bread waste remains a significant issue. The question is: What fundamental solutions exist for the optimal utilization of this strategic product's waste?

Collecting and adequately utilizing bread waste is a strategy that has received little attention from the administrators of Isfahan province in recent years. In fact, in some years, this issue has been entirely overlooked. Over the past few years, a significant portion of the province's bread waste has been sent to recycling centers for fertilizer. However, this process not only incurs high recovery costs but also leads to energy loss and depletion of natural resources. Additionally, it has contributed to the shortage of animal feed in Isfahan, especially during the colder months. Various studies have shown that different types of wheat loss and its byproducts, including bread waste, are rich in nutrients and, with modern technologies, can be safely processed into animal feed without compromising animal growth or health. For instance, bread waste from bakeries, confectioneries, and bread production factories can be easily incorporated into the diet of livestock such as cattle and sheep. Moreover, by raising public awareness and implementing proper waste management practices, household bread waste can be separated from urban waste, collected efficiently, and repurposed as feed for livestock and poultry. Currently, bread waste in

Isfahan province amounts to approximately 30,194 tons, of which 6,944 tons are used as animal feed, while 23,248 tons are sent to recycling centers. Only about 23% of the total bread waste is utilized as animal feed. However, as shown in Table 14, by reducing bread waste by just 1% and increasing the percentage converted into animal feed to 70%, it would be possible to address the issue of animal feed shortages and significantly reduce the high costs associated with recycling. Based on the results obtained from the above tables, out of the total wheat demand of the province, which is approximately 650,000 tons, around 63,000 tons are easily wasted. To elaborate, it should be noted that the wheat loss coefficient due to transportation (lcv) in our country is 0.0002 tons per kilometer. Consequently, as shown in Table 12, approximately 8,615 tons of wheat are lost during transportation in Isfahan province. Furthermore, since the majority of combined harvesters used in this province are outdated, approximately 25,604 tons of wheat are lost during harvesting, as indicated in Table 13. Finally, considering that the bread waste rate in this province is 5%, about 30,194 tons of bread are wasted, as shown in Table 14. Given the conversion coefficients of wheat to flour and flour to bread, this wasted bread equals approximately 28,615 tons of wheat. According to the obtained results, if the wheat loss coefficient due to transportation (lcv) in this province can be reduced to the global standard of 0.00005, modern combine harvesters are utilized in the fields, and the bread waste rate is decreased by just 1% (referred to as the achievable new condition), a significant wheat saving of 15,000 tons can be achieved. The relevant details are presented in Figure 4.

**Table 14.** The bread waste in Isfahan province ( $\frac{\text{tons}}{\text{year}}$ )

Percentage of bread waste	The amount of bread waste	The amount of animal food	Amount of wheat lost except for animal feed
5%	30194	6944	23248
4%	24154	18599	5554



**Figure 4.** Comparison of the current situation of wheat loss in Isfahan province and the new situation that can be achieved.

## 8. Managerial Insights

- This study provides several important managerial and policy-related insights based on the optimization results and sensitivity analysis of the wheat supply chain in Isfahan Province:
- **Prioritize Investment in Modern Harvesting Equipment:** The use of outdated combine harvesters results in significantly higher wheat losses (5.7%) compared to modern machines (1.67%). Replacing these older machines or offering financial incentives to encourage farmers to adopt newer equipment can substantially reduce post-harvest losses and improve overall supply chain efficiency.
- **Enhance Transportation Practices:** Wheat loss during transportation (0.0002 tons per ton-kilometer) is four times higher than the global standard (0.00005). To address this issue, managers should implement improved vehicle sealing techniques, enforce proper handling protocols, and consider upgrading the transportation fleet. These measures can help reduce product loss, operational costs, and environmental emissions.
- **Optimize Bread Waste Utilization:** Bread waste currently amounts to over 30,000 tons annually, of which only approximately 23% is repurposed as animal feed. By reducing bread waste by just 1% and increasing its conversion rate to animal feed to 70%, more than 15,000 tons of wheat could be saved. Authorities should invest

in household-level awareness campaigns, implement separate waste collection systems, and develop animal feed processing facilities to enhance utilization.

- **Support Strategic Infrastructure Expansion:** The optimization model consistently demonstrates benefits from constructing one new silo and one waste collection center. These investments reduce costs and waste while generating employment opportunities, thereby supporting both economic and social sustainability goals.
- **Use Decision-Support Models in Policy Planning:** Multi-objective optimization methods—such as the MILP model with the  $\epsilon$ -constraint method employed in this study—enable more effective trade-off analyses among cost, environmental impact, and social benefits. Local and national decision-makers can adopt similar models to support sustainable planning of agricultural supply chains.

## 9. Discussion and future research

Climate change, drought, soil degradation, and environmental destruction affect global food production. These challenges, along with the rapidly growing population, have heightened the importance of food security more than ever before. Understanding sustainability factors and reducing food loss and waste can help expand perspectives on managing food demand in human societies sustainably. This study considers a comprehensive design for the sustainable supply chain of the strategic wheat product. A mixed-integer linear programming (MILP) model is proposed to achieve this. This model aims to minimize losses and waste throughout the wheat supply chain while addressing environmental, economic, and social aspects. From an environmental perspective, it seeks to reduce greenhouse gas emissions; from an economic perspective, it aims to lower total network costs (such as production, storage, transportation, and facility establishment costs); and from a social perspective, it focuses on creating job opportunities through the establishment of new facilities. Additionally, the model incorporates animal feed centers, waste collection, recovery, and disposal facilities. Special attention has been given to minimizing wheat loss, not only at the harvesting stage—whether by sickle or combine harvester—but also through proper transportation planning for wheat and its byproducts (such as flour) using suitable vehicles. In this study, the developed multi-objective model was solved using the epsilon-constraint method. The model's efficiency was evaluated using real data from the wheat supply chain in Isfahan province. The model's results, along with the sensitivity analysis conducted on various influencing parameters, demonstrated that with better planning and management in this supply chain, a significant reduction in wheat loss and waste, as well as its byproducts, can be achieved. Based on the literature review and the proposed model in this study, future research on the sustainable supply chain of products such as wheat and grains should account for both intentional and unintentional disruptions in supply and demand during the design phase. Additionally, given the decline in wheat quality due to improper storage conditions and moisture loss, factors such as the dormancy period of wheat and appropriate storage methods in silos and warehouses should be incorporated into the corresponding models. Furthermore, considering the effectiveness of the model using Isfahan-specific data, the proposed methodology can be extended to other provinces facing similar challenges, with appropriate adaptation of the input parameters.

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