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Designing and planning a rice supply chain: a case study for Iran farmlands

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A B S T R A C T

Agricultural food supply chains of different grains such as wheat, rice, and corn include several processes from cropping and harvesting to distribution. Integrating these processes to reduce costs, in addition to providing sufficient supply, are of the major goals of agri-food supply chain management. Rice is an important grain that constitutes an important part of people's diets throughout the world. FAO predicts that global rice utilization would increase over the next few years. Considering rice's importance, in this paper, a mixed-integer linear mathematical model for designing and planning of rice supply chain is proposed which aims to maximize total profit by integrating different decisions of the rice supply chain including supplier selection, cropping, fertilizing, pest control, harvesting, milling, transportation, and distribution. This model considers different rice varieties and takes into account irrigation water requirements of crops and available water resources. A case study of Iran farmlands in Gilan province is employed to show the applicability and advantages of the proposed model for the rice supply chain. Results indicate that increasing conversion ratio of paddy to rice and reducing labor costs would have a significant impact on the total profit of the supply chain.

1. Introduction

Food is an important product all around the world and is produced in different forms. As Van Wart et al. (2013) declared, it is straightforward that the more world population is, the more food consumption. It is estimated that there will be a 35% increase in population by 2050. Therefore, it could be concluded that, as resources become scarce, access to food decreases. Iran is the second-largest country in the Middle East and its territory spans 1,648,195 km^2. About one-third of Iran's land area is proper for farmland, although prominent areas are not cultivable due to lack of water resources and poor soil (low nutrients, high salts and not rich in organic matter). In Iran, agriculture consumes 86 billion cubic meters of 94 billion cubic meters of harvested water (91.5%) which is higher than the global average. Also, FAO in country Programming Framework (2012) reported that irrigation consumes about 92% of groundwater that can cause water shortage and soil salinity in the future. Rice as an important grain that constitutes an important part of people's diet throughout the world, can be undoubtedly considered as a staple food. Financial Tribune (2015) reported that rice consumption in Iran is 7 times more than the European Union with an annual consumption equal to 36.6 kg per capita, in contrast to 5.3 kg for EU members. As many people consume it, the state of quality and healthiness are under public scrutiny. To guarantee the quality and healthiness of the food, the process of farm to fork should be put under consideration. Also, since rice is a staple food, its supply should be planned carefully in order to

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guarantee food security. Mangan and Christopher (2005) stated that designing a well-defined supply chain of agri-food not only ensures the continuity of rice supply but also ensures the consumers and the authorities that the products are healthy.

This paper aims to design and plan the rice supply chain in a way that takes cropping, milling, and distribution into account. Optimizing different decisions such as determining the optimal flow between different stages of the supply chain, the amount of area under cultivation, and milling center selection are under consideration. Integrating the stages of the supply chain in the provided mathematical model prevents obtaining sub-optimal solutions. As rice is a staple food in Iran, a case study is conducted to validate the proposed model and show its application in real-life situations.

The rest of this paper is organized as follows: First, the related researches are reviewed to find the research gap in section 2. Then the problem is described in detail to present the framework of research in section 3. The mathematical formulation is stated in section 4. The case study is presented in section 5 in detail. Then, the results and the sensitivity analyses are discussed in sections 6 and 7, respectively. Finally, conclusions and future research opportunities are provided in section 8.

2. Literature review

Supply chain management is a set of approaches used to coordinate suppliers, manufacturers, warehouses, and retailers in order to minimize costs (or maximize profits) in addition to maintaining customer service levels. Agri-food supply chains are composed of different processes that are responsible for bringing food from farm to fork. These processes include cultivation, harvesting, processing, and distribution. Agri-food supply chains have received the attention of many researchers, and there is a rich body of literature in this area. Clarke (1989) presented a mathematical model to determine the optimal cropping pattern in order to maximize the return from agricultural land. The objective function was to maximize total profit. Diversifying crops on land is an important tool that can increase the return from the agricultural land. Additionally, using proper seed, fertilizer, and pesticide plays an important role in making healthy products. Annetts and Audsley (2002) considered the problem of cropping by developing a multi-objective mathematical model for different agricultural conditions. In this paper, the objective function is maximizing total profit. Moreover, inventory control, and perishability of products are taken under consideration.

Higgins and Laredo (2006) investigated harvesting, and transportation decisions of the sugar supply chain in Australia. Since Australian sugar industry suffers from financial problems, the proposed model aims to minimize total costs. Ferrer et al. (2008) examined the harvest-scheduling problem, and provided a heuristic solution approach for the mixed-integer linear model. Additionally, labor allocation, and routing decisions are considered. A quality loss function was used to optimally determine harvest date, and a real case study was presented in this research. Aryanezhad and Jabbarzadeh (2009) presented a paper regarding integrated inventory-location model with random disruption. The author addressed the problem of supply chain design when distribution centers were liable to random disruption, meaning one or more distribution centers could be unable to provide service at any time. They formulated the model with the objective function of minimizing inventory, shipping, and sales costs. To solve the model, the authors used the genetic algorithm. Ali et al. (2009) presented the problem of infield logistics, and formulated it as an integer linear programming vehicle routing problem. The vehicle operations are carried out in order to perform crop harvesting. Piewthongngam et al. (2009) investigated the problem of lack of integration between farms, and milling centers, which leads to excessive supply to milling centers (more than their capacities). To optimally plan farms, and milling centers, cultivation planning was conducted to determine the cultivation time, cultivar selection, and harvesting time. The objective function was maximizing total sugar production and a case study of milling in Thailand was considered. Blanco et al. (2010) investigated the cooperation in the agriculture supply chain in the field of maize, and forage harvesting. In this problem, a linear mixed-integer programming model is proposed aiming to minimize the total working time of machines.

Cai et al. (2010) examined the problem of optimization, and coordination of fresh agricultural food supply chain. The considered network has long haul transportations. However, the distributor must use an appropriate method to keep the products fresh. Therefore, to determine order quantity, centralized and decentralized states of coordination have been examined to maximize total manufacturer and distributor profits. Bohle et al. (2010) developed a robust optimization model for scheduling the harvesting of grapes. Due to existing uncertainties in phenomena, it is important to develop a model that enhances productivity, and improves the situation at the harvest stage. The developed robust optimization model was solved for a real case problem. Márquez et al. (2011) examined a multi-objective crop planning problem, and optimized the model using a pareto-based evolutionary algorithm. Due to the importance of saving water resources, the proposed model maximizes total profit while minimizing water consumption. In this problem, real data is collected from several greenhouses in Spain. Zhang and Li (2012) presented an e-business-based agri-food supply chain to optimize internal costs, and productivity. In fact, they used RFID technology for information sharing to coordinate the supply chain.

Tan and Çömden (2012) examined the annual agricultural cropping pattern considering harvest, and yield risk. This study presented a planning approach for a company that aims to estimate annual supply. The goal was to maximize profits, and a contract was used to coordinate supply chain members. Esmaeilikia et al. (2016) proposed new approaches for supply chain flexibility to deal with operational risks. In fact, the contribution of this paper was to deal with supply chain risks using a flexible approach while taking into account disruptive risks. The paper's supply chain includes suppliers, factories, distribution centers, and end customers. Madadi et al. (2014) proposed a model concentrating on the quality of raw materials that can affect the whole supply chain. In this paper, the reduction in the amount of contaminated raw material by manufacturer is examined. The proposed model considers strategic decisions as well as tactical ones, and aims to minimize total costs.

Thoucharee et al. (2017) presented a mathematical model for rice inventory planning and transportation from farms to milling centers, and from milling centers to export and wholesale ports. The results are obtained using a meta-heuristic algorithm. Hossain and Jahan (2018) assessed the weaknesses of the informal rice milling industry in Bangladesh. They also examined the benefits of creating centralized and specialized industrial zones. These centralized industrial areas can be created by clustering. Ahmadi et al. (2018) presented models of decision support systems for fresh fruits and vegetables in order to plan and coordinate the related supply chain in strategical, tactical and operational levels. The objective is to maximize profit. Cheraghalipour et al. (2019) considered the rice supply chain and provided a bi-level model for rice supply chain management. The objective function is to minimize total cost. The authors used meta-heuristic algorithms to optimize the proposed NP-hard problem.

Based on the literature review, the following contributions will be considered in this paper. The comparison of the present study with the previous researches is presented in Table 1.

- This study considers irrigation water consumption, since reducing surface and groundwater withdrawal is an important national issue;
- This paper integrates all the decisions related to the supply chain in order to avoid sub-optimality. To the best of our knowledge, there are few studies that consider all processes from farm to fork.
- The combination of fertilizers required for growing rice in each region is considered in this paper;
- The pesticide needed for growing rice in each region is taken into consideration.

Table 1

Comparison of present research vs. recent studies

		Decisions						Objective function(s)							
Author(s)	**Year**	Cropping	Milling	Seed supplier selection	Irrigation water consumption	Inventory planning	Distribution	Maximizing Profit	Minimizing Costs	Maximizing sustainability	Minimizing water usage	Minimizing working time	Maximizing production	**Case study**	**Solution method**
Clarke	1989	√						√						√	E
Annetts	2002	√						√		√				√	E
Higgins	2006								√					√	H
Ferrer	2008								√					√	H
Ali	2009	√							√			√			E
Piewthongngam	2009	√											√	√	H
Blanco	2010											√			H
Cai	2010						√		√						D
Bohle	2010								√						S
Marquez	2011	√			√			√			√			√	MH
Tan	2012	√						√						√	E
Thoucharee	2017						√		√						MH
Hossain	2018		√						√					√	E
Ahmadi	2018	√						√							E
Cheraghalipour	2019					√	√		√						MH
This paper	2019	√	√	√	√	√	√	√						√	E

S: Simulation, E: Exact, MH: Meta-heuristic, H: heuristic, D: Differentiation

3. Problem statement

Consider a single farming company (Nahid Aseman Iranian Co.), which specializes in the cultivation, production, and distribution of rice. The rice supply chain includes the stages of cropping, milling, and distribution. This company's supply chain network is shown in Fig. 1.

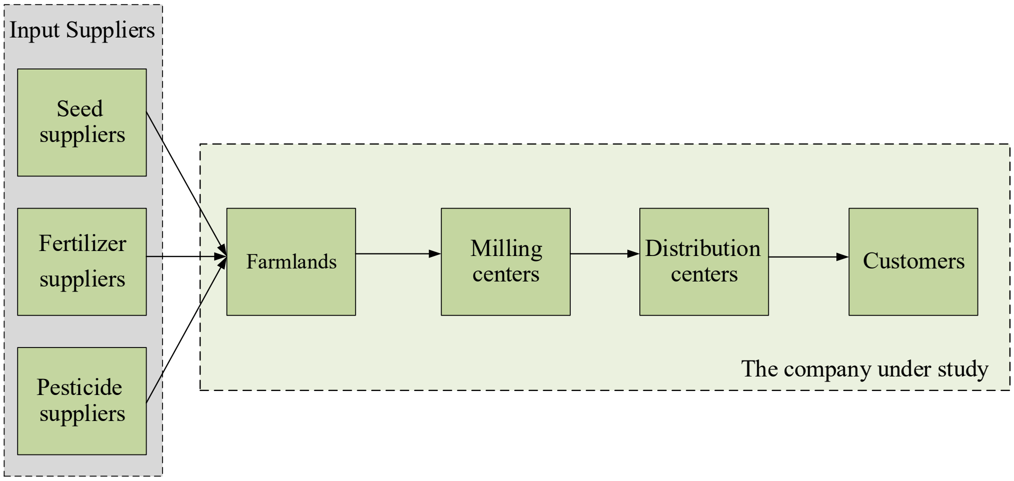


Fig. 1. The rice supply chain network of the company understudy

This company owns agricultural lands in different regions. As rice varieties differ in yield, irrigation requirements, and costs, this company aims to determine the best cropping pattern to maximize profit. The cultivation process includes land preparation, seed sowing, irrigation, fertilization, and pest control. After harvesting, paddies are transported to milling centers where they are converted to final products including rice, broken rice, bran, and husk. Then final products are transported to distribution centers where they are held and transported to customers. The company should make integrated decisions for cropping, milling, and distribution to avoid sub-optimality. A mathematical model is formulated to simultaneously make decisions regarding the whole supply chain. These strategic and tactical decisions are listed in the following:

- Selecting the varieties of rice for cropping
- Selecting the regions to crop, and determining the area under cultivation
- Supplier selection for seeds, fertilizers, and pesticides
- Selecting milling centers
- Transportation, and distribution planning

4. Mathematical formulation

Model assumptions are as follows:

- Seeds, fertilizers, and pesticides are provided by suppliers when they are needed. In other words, the company does not store seeds, fertilizers or pesticides.
- Irrigation water requirements, fertilizers, and pesticides needs of crops must be fully satisfied.
- Milling centers differ in conversion ratio since they use different technologies.
- Required labor for cultivation and harvesting of rice is independent of the variety of cultivated rice.
- A different combination of fertilizers is required for growing rice in each region.
- A different combination of pesticides is required for growing rice in each region.
- Total irrigation water requirements cannot exceed the available amount of surface and groundwater.

The mathematical model involves indices and sets, parameters, decision variables, objective functions, and the constraints, which are presented in the following.

4.1 Indices and sets

$i \in \{1,2,3,4,5\}$	Rice varieties
$l \in \{1,2,3\}$	Regions
$f \in \{1,2,3\}$	Fertilizers
$p \in \{1,2\}$	Pesticides
$m \in \{1,\ldots,M\}$	Milling centers
$d \in \{1,\ldots,D\}$	Distribution centers
$e \in \{1,\ldots,E\}$	Customer zones
$r \in \{1,2,3\}$	Final products (Rice, broken rice and bran)
$s \in \{1,\ldots,S\}$	Suppliers

4.2 Parameters

YLD_{il}	Yield of rice variety i in region l
IW_{il}	Irrigation requirement of rice variety i in region l
ASW_l	Available surface water in region l that can be dedicated to irrigation
AGW_l	Available groundwater in region l
Mg_l	Groundwater mining allowance coefficient in region l
η_l	Irrigation efficiency in region l
CSW_l	Cost of surface water in region l
CGW_l	Cost of groundwater in region l
A_l	Available irrigation land in region l

CL_l	Cost of land preparation in region l
CS_l	Sowing cost of rice in region l
CH_l	Harvesting cost in region l
SA_i	The amount of seed required for the cultivation of rice variety i
PS_{is}	Purchasing cost of seed i from supplier s
FA_{ilf}	The amount of fertilizer type f required for growing rice variety i in region l
PF_{fs}	Purchasing cost of fertilizer type f from supplier s
CP_{ps}	Purchasing cost of pesticide type p from supplier s
PA_{ilp}	The amount of pesticide type p required for rice variety i in region l
CLB_l	Labor cost in region l
LC	Required labor for cultivation and harvesting of rice
TCS_{sl}	Transportation cost of rice seeds from supplier s to region l
TCF_{sl}	Transportation cost of fertilizers from supplier s to region l
TCP_{sl}	Transportation cost of pesticides from supplier s to region l
TC_{lm}	Transportation cost of paddy from region l to milling center m
TC'_{md}	Transportation cost of final products form milling center m to distribution center d
TC''_{de}	Transportation cost of final products from distribution center d to customer e
D_{re}	Demand of customer e for product type r
PR_{re}	Selling price of product type r to customer e
CAP_d	Handling capacity of distribution center d
II_{rd}	Initial inventory of product type r in distribution center d
$CAPM_m$	Capacity of milling center m
$CAPS_{is}$	Capacity of supplier s for providing rice seed i
$CAPF_{fs}$	Capacity of supplier s for providing fertilizer type f
$CAPP_{ps}$	Capacity of supplier s for providing pesticide type p
H_{rd}	Holding cost of product type r in distribution center d
PRO_m	Processing cost at milling center m
α_{rm}	Conversion ratio of paddy to final product r in milling center m

4.3 Decision variables

SW_l	Amount of surface water used for irrigation in region l
GW_l	Amount of groundwater used for irrigation in region l
XS_{isl}	Quantity of rice seed i transported from supplier s to region l
XF_{fsl}	Quantity of fertilizer f transported from supplier s to region l
XP_{psl}	Quantity of pesticide p transported from supplier s to region l
XC_{il}	Planting area of rice variety i in region l
X_{ilm}	Quantity of paddy type i transported from region l to milling center m
X'_{rmd}	Quantity of final product type r transported from milling center m to distribution center d
Y_{rde}	Quantity of final product type r transported from distribution center d to customer zone e
I_{rd}	Final inventory of product type r in distribution center d
Z_m	1 if milling center m is used for processing

4.4 Mathematical model

The objective function maximizes total profit in Eq. (1) to Eq. (10). Eq. (1) is Sales revenue. Eq. (2) is the cost of purchasing and transportations of rice seeds. Eq. (3) presents the costs of purchasing and transportation of fertilizers. Eq. (4) is the cost of purchasing and transportation of pesticides. The Cost of transporting paddies to milling centers is presented in Eq. (5). Eq. (6) shows the cost of transporting final products to distribution centers. Eq. (7) is the cost of transporting final products to customers. Eq. (8) shows the holding costs in distribution centers. Eq. (9) is the processing costs in milling centers. Finally, Eq. (10) is the costs of land preparation, seed sowing, harvesting, labor work, and water

$$max\ OBJ = \sum_r \sum_d \sum_e PR_{re} \cdot Y_{rde} \tag{1}$$

$$-\sum_i \sum_s \sum_l (PS_{is} + TCS_{sl}) \cdot XS_{isl} \tag{2}$$

$$-\sum_f \sum_s \sum_l (PF_{fs} + TCF_{sl}) \cdot XF_{fsl} \tag{3}$$

$$-\sum_p \sum_s \sum_l (CP_{ps} + TCP_{sl}) \cdot XP_{psl} \tag{4}$$

$$-\sum_i \sum_l \sum_m TC_{lm} \cdot X_{ilm} \tag{5}$$

$$-\sum_r \sum_m \sum_d TC'_{md} \cdot X'_{rmd} \tag{6}$$

$$-\sum_r \sum_d \sum_e TC''_{de} \cdot Y_{rde} \tag{7}$$

$$-\sum_r \sum_d H_{rd} \cdot I_{rd} \tag{8}$$

$$-\sum_i \sum_l \sum_m PRO_m \cdot X_{ilm} \tag{9}$$

$$\begin{aligned} &-\sum_i \sum_l [CL_l + CS_l + CH_l + CLB_l \cdot LC] \cdot XC_{il} \\ &-\sum_l (CSW_l \cdot SW_l + CGW_l \cdot GW_l) \end{aligned} \tag{10}$$

subject to

$$\sum_r \sum_m X'_{rmd} \le CAP_d \qquad \forall d \tag{11}$$

$$\sum_i \sum_l X_{ilm} \le CAPM_m \cdot Z_m \qquad \forall m \tag{12}$$

$$Z_m \le \sum_i \sum_l X_{ilm} \qquad \forall m \tag{13}$$

$$\sum_d Y_{rde} \le D_{re} \qquad \forall r, e \tag{14}$$

$$II_{rd} + \sum_m X'_{rmd} - \sum_e Y_{rde} - I_{rd} = 0 \qquad \forall r, d \tag{15}$$

$$\sum_d X'_{rmd} = \sum_i \sum_l \alpha_{rm} \cdot X_{ilm} \qquad \forall r, m \tag{16}$$

$$\sum_i XC_{il} \le A_l \qquad \forall l \tag{17}$$

$$SW_l \le ASW_l \qquad \forall l \tag{18}$$

$$GW_l \le Mg_l \cdot AGW_l \qquad \forall l \tag{19}$$

$$\sum_i IW_{il} \cdot XC_{il} - \eta(SW_l + GW_l) \le 0 \qquad \forall l \tag{20}$$

$$\sum_s XS_{isl} = SA_i . XC_{il} \qquad \forall i, l \tag{21}$$

$$\sum_l XS_{isl} \le CAPS_{is} \qquad \forall i, s \tag{22}$$

$$\sum_{s} XF_{fsl} = \sum_{i} FA_{ilf} \cdot XC_{il} \qquad \forall f, l \qquad (23)$$

$$\sum_{l} XF_{fsl} \leq CAPF_{fs} \qquad \forall f, s \qquad (24)$$

$$\sum_{s} XP_{psl} = \sum_{i} PA_{ilp} \cdot XC_{il} \qquad \forall p, l \qquad (25)$$

$$\sum_{l} XP_{psl} \leq CAPP_{ps} \qquad \forall p, s \qquad (26)$$

$$\sum_{f} YLD_{ilf} \cdot XC_{il} = \sum_{m} X_{ilm} \qquad \forall i, l \qquad (27)$$

$$SW_l, GW_l, XS_{isl}\ XF_{fsl}, XP_{psl}, XC_{il}, X_{ilm}, X'_{rmd}, Y_{rde}, I_{rd} \geq 0,\ Z_m \in \{0,1\} \qquad (28)$$

Constraint (11) ensures the handling capacity constraint of distribution centers. The processing capacity of operating milling centers is shown in constraint (12). Quantity of transported final products to each customer zone cannot exceed its demand, which is presented in constraint (14). Constraint (15) guarantees that the outflow of distribution centers cannot exceed the inventory on hand. Constraint (16) calculates the quantity of final products based on the conversion ratio of milling centers. Maximum available land is presented in constraint (17). Surface water constraint is presented in (18). Constraint (19) presents the maximum available groundwater resources in each region. Constraint (20) calculates the irrigation water requirements in each region. Constraint (21) calculates the required quantity of rice seeds. Constraint (22) shows the maximum capacity of each supplier for providing rice seeds. Constraint (23) calculates the required quantity of fertilizers and constraint (24) is the maximum capacity of each supplier for providing each fertilizer. Constraint (25) calculates the required quantity of pesticides and constraint (26) is the maximum capacity of each supplier for each pesticide. Constraint (27) determines the amount of harvested paddies. The last constraint (28) determines decision variables and their types.

5. Case study

In this section, a real case of Iran farmlands (Nahid Aseman Iranian Co.) is considered to validate the proposed model and investigate its applicability in real-life situations. This company cultivates five rice varieties consisting of three local types and two high-yield types. Also, three final products are extracted from rice paddies including rice, broken rice, and bran and husk. Nahid Aseman Iranian Co. has six major customers, which differentiate in demand and selling price. The prices are presented in Table 2.

Table 2
Selling price of final products in each customer zone (Iranian Million Rial/tonnes)

Final product	Customer					
	1	2	3	4	5	6
Rice	90	90	100	100	120	0
Broken rice	45	45	50	50	60	120
Bran and husk	0	0	0	0	0	110

The area of the company's farmlands is listed in Table 3. These lands are all placed in Gilan province. However, Gilan province is divided into three sections: center, west, and east as shown in Fig. 2. Moreover, this company has three major distribution centers in the center, west, and east of Gilan province. Additionally, Three main suppliers are considered in this paper including 1) Local suppliers 2) Agricultural Support Services Co. 3) Wholesalers.

Table 3
Area and preparation cost of farmlands

Province	Regions	Area(ha^2)	Price (Iranian Million Rial)
Gilan	Center	1000	15
	West	500	15
	East	5000	15

The irrigation water requirement of each rice variety, which depends on the land's location is presented in Table 4. The available surface and groundwater resources in Gilan and annual milling allowance coefficient from groundwater recourses in each region can be observed in Table 5.

Table 4
Irrigation water requirement of each rice variety (m^3/ha)

Rice varieties/Section		Center	West	East
Local	1	9000	8000	9000
	2	9000	8000	9000
	3	9000	8000	9000
High-yield	4	10000	9000	10000
	5	10000	9000	10000

Fig. 2. Sections (regions) of Gilan province, Iran

Table 5
Available water resources and Groundwater mining allowance coefficient in each region

Province	Section	Water resources (m^3)				
		Surface water		Groundwater		
		Available resource (m^3)	Cost (Iranian Rial)	Available resource (m^3)	Milling allowance coefficient	Cost (Iranian Rial)
Gilan	Center	14347826	650	2057971	0.75	1667
	West	3175676	650	3452703	0.14	1667
	East	34210526	650	16894737	0.21	1667

Irrigation efficiency (water application efficiency) is considered 0.6 in the center of Gilan, 0.5 in the western section, and 0.5 in the eastern section. To deter, incapacitate, kill or discourage pests, chemical or biological pesticides are used. The procurement prices of pesticides are presented in Table 6.

Table 6
Pesticides' suppliers and prices (Iranian Rial per kg)

Pesticide/Supplier	Agricultural Support Services Co.	Wholesalers
1	1950000	1950000
2	3400000	3400000

Moreover, fertilizer is a chemical or natural substance added to soil or land to increase its fertility. Fertilizers' details can be observed in Table 7.

Table 7
Fertilizers' suppliers and prices (Iranian Rial per kg)

Fertilizer/Supplier	Agricultural Support Services Co.	Wholesalers
Urea	8600	8600
Potassium Sulfate	11200	11200
Triple Super Phosphate	15000	15000

The demand of each customer zone for final products is listed in Table 8.

Table 8
Demands of each customer zone for final products (tonnes)

Product/Customer zone	1	2	3	4	5	6
Rice	5000	3000	1500	2000	100000	0
Broken rice	0	0	0	0	0	100000
Bran and husk	0	0	0	0	0	100000

The conversion ratio of paddy to final products is listed in Table 9.

Table 9
Conversion ratio of paddy to final products

Product	milling center		
	1	2	3
Rice	0.6	0.6	0.6
Broken rice	0.2	0.2	0.2
Bran and husk	0.1	0.1	0.1

Paddies are processed at milling centers. The capacity of milling centers can be observed in Table 10.

Table 10
Capacity of milling centers (tonnes)

Milling center	Capacity
1	8000
2	2500
3	12000

The yield of rice varieties in each region and the procurement prices of rice seeds from each supplier is presented in Table 11.

Table 11
Yield of rice varieties, and procurement price of rice seeds (tones/ha^2)

Rice variety		Price (Iranian Rial)		Gilan		
		Local suppliers	Agricultural Support Services Co.	Center	West	East
Local	1	80000	100000	2.1	2.1	2.1
	2	70000	90000	2.1	2.1	2.1
	3	65000	80000	2.1	2.1	2.1
High-yield	4	65000	75000	3	3	3
	5	63000	70000	3	3	3

6. Computational results

The proposed mathematical model is solved using GAMS 24.7.4 on a computer with Intel® Core™ i7-6500U 2.5 GHz, and 16GB DDR4 Memory. The data used is provided in the previous section. The results of the model are presented in the following. The optimal value of the objective function is 3.078×10^{11}. This value is the total profit of the supply chain. In the optimal solution, only one of the high-yield varieties (rice variety 5) is cultivated. Moreover, all available land is used for cropping. The results are presented in Table 12. Also, 87% of milling capacity is used in the optimal solution. The optimal flows of paddies between farmlands and milling centers are presented in Table 13.

Table 12
Optimal planting area (ha^2)

Rice variety	Regions		
	Center	West	East
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	1000	500	5000

Table 13
Optimal paddy flow between farmlands (regions) and milling centers

Region	Rice variety 5		
	MC 1	MC 2	MC 3
Center	3000	0	0
West	1500	0	0
East	500	2500	12000

Surface water withdrawal for irrigating crops in each region is presented in Table 14. As can be seen, surface water resources are sufficient for irrigation requirements completely. Therefore, Groundwater resources are not used

Table 14

Water withdrawal (m^3)

Region	**Surface water**	**Groundwater**
Center	3333333	0
West	1800000	0
East	20000000	0

The optimal flows of products between milling centers and distribution centers are presented in Table 15. The optimal flows of products from distribution centers to customer zones are presented in Table 16. Also, the flow of rice seeds, and fertilizers from suppliers to farmlands are presented in Tables 17 and 18, respectively.

Table 15

Optimal product flows (tones) between milling centers and distribution centers (DC)

Final products	Milling Center	DC 1	DC 2	DC 3
Rice	1	1450	1550	0
	2	1500	0	0
	3	0	0	7200
Broken rice	1	1000	0	0
	2	500	0	0
	3	0	0	2400
Bran and husk	1	500	0	0
	2	0	250	0
	3	0	1200	0

Table 16

Optimal product flow (tones) from distribution centers (DCs) to customer zones

Final products	DC	Customer zone 5	Customer zone 6
1	1	2950	0
	2	1550	0
	3	7200	0
2	1	0	1500
	2	0	0
	3	0	2400
3	1	0	500
	2	0	1450
	3	0	0

Table 17

Amount of seed (kg) supplied to each region

Supplier	Rice seed	Region		
		Center	West	East
Local suppliers	High-yield	45000	22500	225000

Table 18

Amount of fertilizer (kg) supplied to each region

Region	Urea		Potassium Sulfate		Triple Super Phosphate	
	ASSC*	Wholesalers	ASSC	Wholesalers	ASSC	Wholesalers
Center	140000	0	150000	0	0	250000
West	75000	0	50000	0	0	150000
East	725000	0	450000	0	1000000	250000

* **ASSC:** Agricultural Support Services Co.

7. Sensitivity analysis

In this section, sensitivity analyses are performed to assess the impact of the changes in the conversion ratio of paddy to rice, available surface water, and costs (rice seeds, fertilizers, pesticides, labor, processing, and transportation) on total profit, and planting area.

7.1 Effects of changes in conversion ratio

The main final products of paddies are rice, broken rice, and bran & husk. Changes in the conversion ratio of paddy to rice in milling centers are expected to affect the amount of production, and thus the total profit of the supply chain. Fig. 3 shows the profit's trend when the conversion ratio of paddy to rice changes by 10, and 20 percent. As presented in Table 19, it is clear that the total profit is positively correlated with the conversion ratio. Rice and broken rice constitute 80% of the paddies and the ratio of rice and broken rice is dependent on the processing technology used in the milling centers. It is assumed that 10% percent of paddies would be waste and another 10% is bran and husk. Increasing the conversion ratio of paddy to rice requires using new technologies at milling centers such as parboiling. This table shows that a 20% increase in conversion ratio will increase total profit by 82%.

Table 19
Total profit vs. conversion ratio of paddy to final products

Final products	Conversion ratio			
	-10%	0%	+10%	+20%
Rice	0.54	0.6	0.66	0.72
Broken rice	0.26	0.2	0.14	0.08
Bran and husk	0.1	0.1	0.1	0.1
Profit	1.81E+11	3.08E+11	4.34E+11	5.61E+11
Changes in profit (percent)	-41%	0%	41%	82%

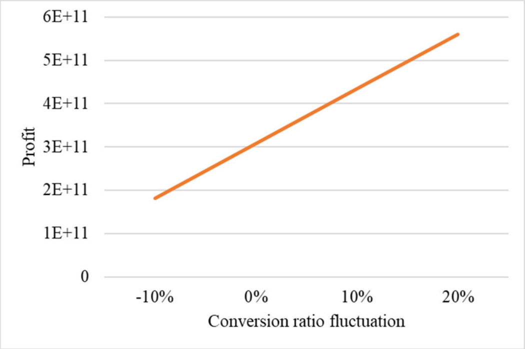


Fig. 3. Total profit vs. conversion ratio

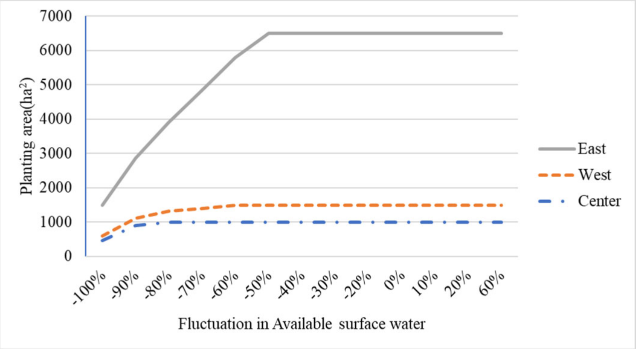


Fig. 4. Optimal planting area vs. available surface water

7.2 Effects of changes in the available amount of surface water

Since water is an essential requirement for growing rice, a reduction in the available amount of water will reduce the optimal planting area since irrigation requirements of crops must be fully satisfied. Fig. 4 shows changes in the optimal planting area when available surface water fluctuates. Rice paddies consume more water than other grains such as wheat and corn, thus a reduction in the available amount of water can highly affect production and total profit. The impact of fluctuations in the available amount of surface water on total profit is presented in Table 20. It should be noted that the total profit does not change by increasing the amount of surface water since the available planting area is limited.

Table 20

Total profit vs. the available amount of surface water

Fluctuation in available surface water	Available surface water			Profit
	Center	West	Earth	
-90%	1,434,782.6	317,567.6	3,421,052.6	1.3E+11
-80%	2,869,565.2	635,135.2	6,842,105.2	1.8E+11
-70%	4,304,347.8	952,702.8	10,263,157.8	2.3E+11
-60%	5,739,130.4	1,270,270.4	13,684,210.4	2.7E+11
-50%	7,173,913.0	1,587,838.0	17,105,263.0	3.05E+11
-40%	8,608,695.6	1,905,405.6	20,526,315.6	3.08E+11
-30%	10,043,478.2	2,222,973.2	23,947,368.2	3.08E+11
-20%	11,478,260.8	2,540,540.8	27,368,420.8	3.08E+11
0%	14,347,826.0	3,175,676.0	34,210,526.0	3.08E+11
10%	15782608.6	3493243.6	37631578.6	3.08E+11
20%	17217391.2	3810811.2	41052631.2	3.08E+11
60%	18652173.8	4128378.8	44473683.8	3.08E+11

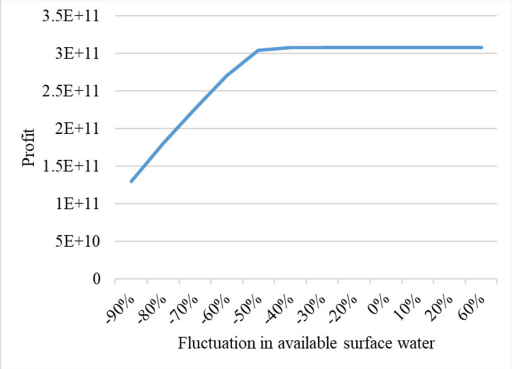


Fig. 5. Profit vs. the available amount of surface water (SW)

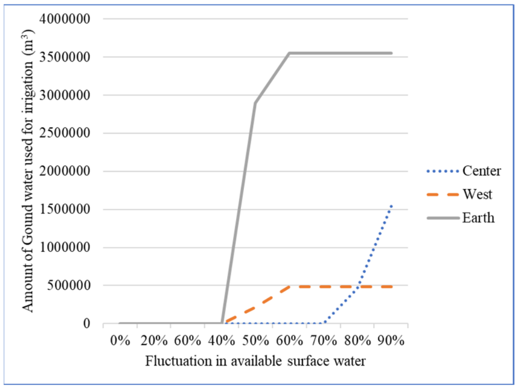
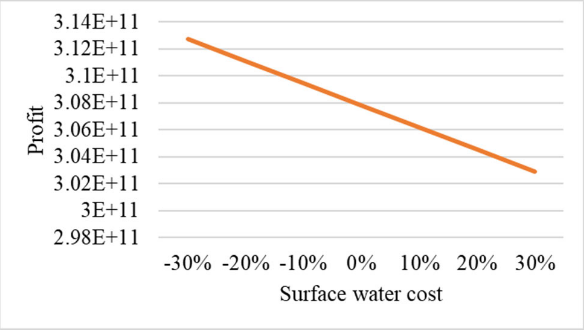


Fig. 6. Groundwater usage vs. the available amount of surface water (SW)

A decrease in the available amount of surface water affects groundwater usage. As shown in Fig. 6, the usage of groundwater starts to increase in different fluctuation points for each region. This analysis is very important as saving groundwater resources in a national issue.

7.3 Effects of costs' fluctuations on total profit

Fig. 7 and Fig. 8 show the impact of changes in water costs on the profit. It can be seen from Table 21 and 22 that the profit is less sensitive to fluctuations in groundwater costs in comparison to surface water costs.



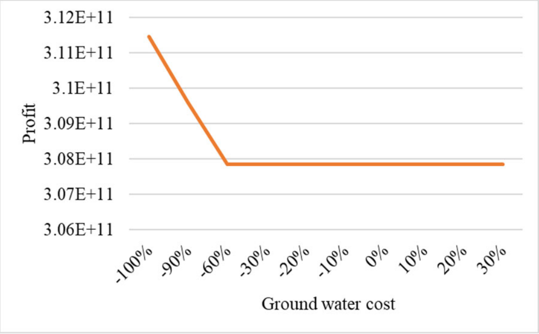


Fig. 8. Total profit vs. surface water cost

Fig. 7. Total profit vs. groundwater cost

Table 21
Total profit vs. fluctuations in the cost of surface water

Fluctuation	Regions			Total profit
	Center	West	Earth	
-30%	455	455	455	3.13E+11
-20%	520	520	520	3.11E+11
-10%	585	585	585	3.09E+11
0%	650	650	650	3.08E+11
10%	715	715	715	3.06E+11
20%	780	780	780	3.05E+11
30%	845	845	845	3.03E+11

Table 22
Total profit vs. fluctuations in the cost of groundwater

Fluctuation	Regions			Total profit
	Center	West	Earth	
-100%	0	0	0	3.11E+11
-90%	333.4	333.4	333.4	3.1E+11
-60%	666.8	666.8	666.8	3.08E+11
-30%	1166.9	1166.9	1166.9	3.08E+11
-20%	1333.6	1333.6	1333.6	3.08E+11
-10%	1500.3	1500.3	1500.3	3.08E+11
0%	1667	1667	1667	3.08E+11
10%	1833.7	1833.7	1833.7	3.08E+11
20%	2000.4	2000.4	2000.4	3.08E+11
30%	2167.1	2167.1	2167.1	3.08E+11

Table 23 shows the effects of fluctuations in seed purchasing cost on total profit. The increase in the purchasing cost of rice seeds has led to a decrease in total profit is shown in Fig. 8. It should be noted that seed purchasing cost did not affect the planting area in this analysis.

Table 23
Total profit vs. fluctuations in seed purchasing cost

Fluctuations in seed purchasing cost	-30%	-10%	0%	10%	40%
Profit	3.13E+11	3.1E+11	3.08E+11	3.06E+11	3.06E+11

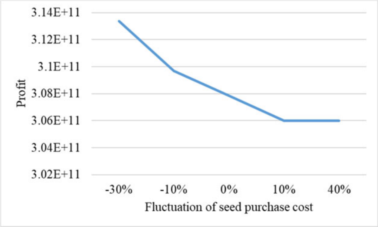


Fig. 8. Profit when seed purchasing cost changes

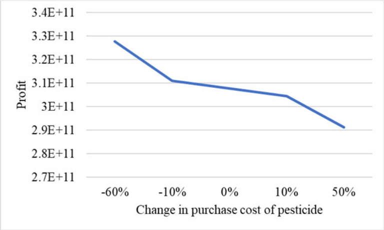


Fig. 9. Profit vs. fluctuations in pesticide purchasing cost

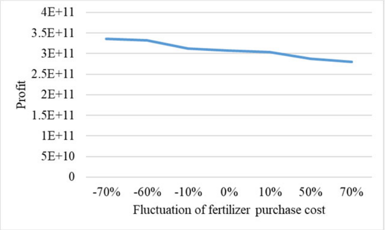


Fig. 10. Profit vs. fluctuations in fertilizer purchasing cost

The increase in pesticide purchasing costs will reduce total profit. Due to the necessity of using pesticides that is indicated in Eq. (25), when pesticide purchasing costs increase, total profit decreases. Also, when fertilizer purchasing cost fluctuates, the behavior of total profit is shown in Fig. 10. The decrease in profit when fertilizer purchasing cost increases, is due to Eq. (23). Labor cost constitutes a substantial portion of total costs, which is about 50% of total costs in the present case. Therefore, an increase in labor cost has a significant impact on total profit as shown in Fig. 11. Using new technologies for production and processing can reduce the required labor and, thus decreases costs.

Also, Table 24 shows the impact of labor cost on total profit. Considering a 30% increase in labor costs decreases profit by 56%.

Table 24
Profit vs. fluctuations in labor cost

	-20%	-10%	0%	10%	30%
Profit	4.24E+11	3.66E+11	3.07E+11	2.5E+11	1.34E+11

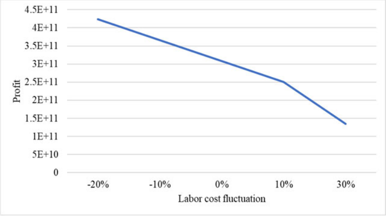


Fig. 11. Profit when labor cost changes

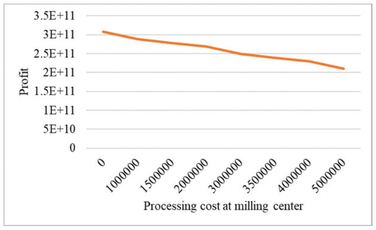


Fig. 12. Sensitivity analysis of processing cost on total profit

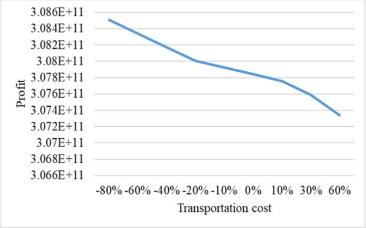


Fig. 13. Profit vs. changes in transportation cost

Fig. 12 shows the impact of changes in processing costs at milling centers on the profit. As the processing cost decreases, the total profit increases. Rice supply chain includes different stages from farmlands to final customers, which requires transportation of products. Therefore, transportation cost is one of the important costs to consider. Fig. 13 shows the total profit when transportation cost changes. It can be seen in this Figure that profit decreases when transportation costs increase. An increase in this cost can affect decision variables such as flow quantities between different facilities, and members of the chain, which reduces production, and profit. The findings of the sensitivity analysis results are presented in the following, which can help managers for decision-making:

- An increase in the conversion ratio of milling centers has a significant effect on total profit. Therefore, investing in new technologies for milling centers such as parboiling is recommended.
- Labor cost constitutes a significant portion of total costs. Therefore, using technologies for cultivation, harvesting, and processing which reduces labor requirements, can reduce costs, and increase total profit.
- Fluctuations in the available amount of surface water can affect the optimal planting area as well. When surface water resources are not sufficient, farmers have to use groundwater which is expensive in comparison to surface water.
- Transportation costs affect the profit of the supply chain. Transportation costs have an effect on the planting area, and thus responsiveness of the chain.

8. Conclusion and future research opportunity

Food is one of the most important needs of human beings which is provided in many forms around the world. Agri-food supply chains are composed of different processes that are responsible for bringing food from farm to fork. These processes include cultivation, harvesting, processing, and distribution. In this paper, a mixed-integer linear mathematical model for designing and planning of rice supply chain has been proposed which aims to maximize total profits by integrating different decisions of the rice supply chain including supplier selection, milling center selection, cropping, fertilizing, pest control, harvesting, milling, transportation, and distribution. This model considers different rice varieties and takes into account irrigation water requirements of crops and available water resources. A case study of Iran farmlands in Gilan province is employed to show the applicability and advantages of the proposed model for the rice supply chain. The sensitivity analysis results show that the conversion ratio of paddy to final products, the available amount of water, and costs (seed, fertilizer, pesticide, labor, and transportation) have different impacts on the total profit and planting area. It is found that the total profit is positively correlated with the conversion ratio. Also, as the available amount of water increases, planting area and final products increase which leads to profit growth. Different analyses are provided for costs' fluctuations to investigate their impacts on total profit. Labor cost constitutes a substantial portion of total costs, which is about 50% of total costs in the present case. It should be noted that an increase in labor costs by 30%, leads to a 56% decrease in total profit. For future studies, considering other decisions such as the location of milling centers and technology selection are recommended. Moreover, future researchers can consider the possibility of contract farming in order to increase planting area and processing capacity. Also, considering different uncertainties that the chain faces can be advantageous.

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