A sustainable rice supply chain planning from the farm to the table: a case study

Seyyed Aziz Seyyed Jifroudi[1], Ebrahim Teimoury*[2], Farnaz Barzinpour[3]

[1] Ph.D. candidate, School of Industrial Engineering, Iran University of Science and Technology, Tehran, Iran
jifroudi2000@yahoo.com -Mobile: 0098 9124570535

[2] Professor, School of Industrial Engineering, Iran University of Science and Technology, Tehran, Iran
Teimoury@iust.ac.ir

[3] Associate Professor, School of Industrial Engineering, Iran University of Science and Technology, Tehran, Iran
barzinpour@iust.ac.ir – Phone Number: 0098 21 73225063

Seyyed Aziz Seyyed Jifroudi is a ph.D. candidate at Industrial Engineering faculty of Iran University of Science and Technology. He is working on rice supply chain.

Farnaz Barzinpour an associate Professor of Industrial Engineering at Iran University of Science and Technology. He teaches meta-heuristics and optimization algorithms.

Ebrahim Teimoury is a Professor of Industrial Engineering at the Iran University of Science and Technology. His field relates to Supply Chain Management, queuing, and Systems Engineering.

Abstract:

Agri-food supply chains include several processes, from cropping and harvesting to distribution. Integrating these processes to reduce costs and environmental impact and providing sufficient supply are the main goals of agri-food supply chain management. Rice, a so-called staple food, makes up a significant portion of the human diet worldwide. Due to the importance of rice, this paper proposes a mixed-integer linear programming model for rice supply chain design and planning that considers economic, environmental, and social dimensions. This model determines the optimal strategic and tactical decisions in the rice supply chain, including cropping pattern, supplier selection, and the location and capacity of new milling centers with parboiling technology. The model considers different rice varieties and irrigation water requirements of crops. Also, it investigates the benefits of renting as well as offering a partnership agreement to independent farmers. A case study of Iran farmlands is employed to show the applicability and advantages of the proposed model for the rice supply chain. To solve the proposed multi-objective model, the ε -constraint method is applied. The results indicate that opening milling centers with parboiling technology is profitable for the supply chain. Moreover, entering a partnership agreement is much more profitable than renting farmlands.

Keywords: Supply chain management, Supply chain network design, Cropping pattern, Milling, Rice supply chain, Sustainability

* Corresponding author; Email: Teimoury@iust.ac.ir; Address: School of Industrial Engineering, Iran University of Science and Technology, Tehran, Iran; Tel.: (+9821)73225022; Mobile: (+98)9123844211

1. Introduction

Rice production, which is the main component of agricultural ecosystems and supports the livelihood security of more than 70% of the population, faces threats of various uncertainties. The supply chain of agricultural products (also known as the agri-food supply chain) has received considerable attention over the past few years due to various reasons, including public awareness of health and pollution of the environment as well as population growth and increased demands. According to Egorov et al. [1], family farms account for about 90% of households in the agricultural sectors which produces a significant volume of production in the world. The need for logical balance among the system performance, environmental, and economical concerns causes an increasing trend of research for circular economies and sustainability [2]. The agri-food supply chain is a network of organizations working together in different processes and activities to bring products and services to the market and satisfy customers' demands [3]. These activities include cultivation, harvest, processing, storage, and distribution.

Ahumada and Villalobos [4] reviewed the papers published between 1985 and 2007. They studied different aspects of the papers, including crop type, planning scope, and modeling approaches. Tsolakis et al. [5] investigated the strategic, tactical, and operational decisions in agri-food supply chains. Kusumastuti et al. [6] investigated the complexities of agri-food supply chains. They reviewed the studies published between 1991 and 2015, focusing on supply chain activities, including cultivation, harvesting, processing, distribution, storage, and transportation.

Biswas and Pal [7] considered multiple goals, including cash expenditure, production, utilization, and profit, then determined the optimal cropping pattern of seasonal crops. Higgins and Laredo [8] examined a sugar supply chain's harvesting and transportation decisions. Lodree Jr and Uzochukwu [9] developed a two-period inventory model for fresh products considering deterioration and stochastic demand. Piewthongngam et al. [10] addressed the lack of milling center capacity in Thailand and proposed a mathematical model to determine cropping and harvest time as well as cultivar selection.

Shiun et al. [11] provided a mixed-integer linear programming model for the optimal planning of the rice milling industry. The proposed model determines optimal network flows, optimal rice husk cogeneration system, and optimal utility of dryers to minimize total costs. An and Ouyang [12] presented a bi-level Stackelberg leader-follower game model to maximize profits and minimize post-harvest loss. Bala et al. [13] investigated the rice supply chain in Bangladesh, which is affected by climate change. The proposed model considers farmers to customers and minimizes total costs under climate change uncertainty. Ahumada and Villalobos [14] provided decision support systems models of fresh fruits and vegetables for planning and coordinating the supply chain's strategic, tactical, and operational decision levels. Cheraghalipour et al. [15] examined the rice supply chain. They presented a bi-level mathematical model for this supply chain to minimize total costs. Carbajal et al. [16] focus on the importance of global supply chains considering the suppliers and farmers of coffee in Peru. They developed a model for evaluating the integration levels of cooperatives and the first-level suppliers to tune sustainability. This strategy enhances volume, product quality, and productivity.

Jifroudi et al. [17] proposed a mixed-integer linear model for designing and planning of rice supply chain that addresses different decisions, including supplier selection, cropping, fertilizing, pest control, harvesting, milling, transportation, and distribution. Pourmohammadi et al. [18] addressed the importing, storage, and distribution decisions in the wheat supply chain of Iran, considering the wheat quality and sleep period. Yan et al. [19] investigated the optimal ordering and coordination of fresh agricultural supply chains based on two-period prices, wholesale prices, option agreements, and cost-sharing agreements.

Phan et al. [20] considered the evaluation of the effect of crop periods and farmlands based on pre-harvest and post-harvest performance. They found that drying periods affect the contamination. Chen et al. [21] examined agri-food supply chains due to the importance of agri-food safety. The effective management and traceability for these products are challenging, so they considered a deep reinforcement learning-based method for profit optimization. Putro et al. [22] studied rice supply chains to identify the related problems and solutions. They examined various databases to find a well-structured approach by supply chain operations Reference (SCOR) theory. Table 1 presents a brief review of the research mentioned above.

Wang et al. [23] investigated problems of circulation and data security in sophisticated rice supply networks to analyze the risks. This study enhances the data tracking and visibility in the network. Elyasi & Teimoury [24] considered the rice supply chain of Iran and used the triple bottom line of sustainability. They developed a framework based on critical systems practice to assess sustainability to determine the final price of rice.

The details of the contributions of this paper are as follows:

- Designing and planning the rice supply chain in a sustainable situation considering economic, environmental, and social impacts.
- The proposed model integrates all the decisions related to the rice supply chain to avoid sub-optimality. As shown in Table 1, very few studies integrated all decisions from the farm to the customer;
- The multi-objective model includes three objective functions such as maximizing profit, minimizing CO_2 emissions, and maximizing the number of job opportunities in milling and distribution centers;
- We investigate the benefits of renting additional agricultural lands as well as offering a partnership agreement to independent farmers;
- In addition to owned milling centers and the possibility of opening new milling centers with parboiling technology, the model can benefit from the capacity of independent milling centers through a cost-plus agreement;
- The model considers two groups of customers with different types of demand (obligatory and non-obligatory).
- One of the contributions of our paper comes from the concept of contract farming which is formulated by considering rented and partnered farmlands in addition to owned farmlands.
- Moreover, we focus on potential milling centers with parboiling technology and independent milling centers which are not covered to this extent in other research.
- Focusing on the customer types, the first group's demand must be satisfied while other customers are ordinary types, for example, industrial and non-industrial customers.

- Product types and rice varieties are also considered in the developed model, e.g., final products such as rice, broken rice, and bran and husk.

International Grains Council [25] predicts that Iran produces about two million tonnes of rice in the 2019-20 crop year. As rice is an essential grain in Iran, its supply chain should be planned carefully to guarantee food security. The rest of this paper is organized as follows: Section 2 describes the problem. The mathematical programming model is formulated in section 3. The application of the mathematical model for the case study is demonstrated in section 4. The results and sensitivity analyses are presented in sections 5 and 6. The last section is dedicated to the conclusion and future research opportunities.

2. Problem statement

A farming company specializes in the cultivation, milling, and distribution of rice. The cultivation process includes land preparation, seed sowing, irrigation, fertilization, and pest control. After harvest, paddies are transported to milling centers, where they dry and convert to final products, including rice, broken rice, bran, and husk. Then, the final products are transported to distribution centers where they are held and transported to customers. Figure 1 represents the company's supply chain.

As shown in Figure 1, this company owns farmlands, milling centers, and distribution centers in different regions and can rent farmlands or offer a partnership contract to independent farmers. The company pays the renting price for rented lands, provides agricultural inputs (seeds, fertilizers, and pesticides), and performs cultivation and harvesting. However, in a partnership contract, the company provides agricultural inputs and purchases the paddies at a pre-determined price after harvest. Also, the company can benefit from the capacity of independent milling centers through a cost-plus contract. Moreover, the company aims to construct one or more milling centers with parboiling technology, with a better conversion ratio than other milling technologies. Strategic and tactical decisions addressed in the proposed model are as follows:

- Selecting the varieties of rice for cultivation
- determining the regions and areas under cultivation (owned, rented, and partnered)
- Supplier selection for seeds, fertilizers, and pesticides
- Selecting milling centers
- Determining the location and capacity of new milling centers with parboiling technology
- Transportation, storage, and distribution planning

3. Mathematical formulation

- The company does not store seeds, fertilizers, or pesticides and supplies them on demand.
- A different combination of fertilizers and pesticides is required for growing rice in each region.
- Total irrigation water requirements cannot exceed the available surface water and groundwater.
- All owned farmlands should be cultivated.
- Milling centers may differ in conversion ratio since they use different processing technologies.
- Labor required for the cultivation and harvesting of rice is independent of the variety of cultivated rice.

- The customers are of two types. The demand for the first group of customers must be satisfied while fulfilling the demand for the second group is not obligatory.

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

3.1. Indices and sets

$i \in \{1,2,3,4,5\}$	Rice varieties
$l \in \{1,2,3\}$	Regions
$o \in \{1,2,3\}$	Farmland type (owned, rented, and partnered)
$f \in \{1,2,3\}$	Fertilizers
$p \in \{1,2\}$	Pesticides
$m_1 \in \{1,...,M_1\}$	Milling centers owned by the company
$m_1 \in \{1,...,M_2\}$	Potential milling centers with parboiling technology
$m_1 \in \{1,...,M_3\}$	Other (independent) milling centers
$m \in \{m_1 \cup m_2 \cup m_3\}$	All Milling centers
$c \in \{1,2,3\}$	Capacity level of potential milling centers
$d \in \{1,...,D\}$	Distribution centers
$e_1 \in \{1,...,E_1\}$	The first group of customers which their demand must be satisfied
$e_2 \in \{1,...,E_2\}$	Other customers
$e \in \{1,...,E\}$	All customers
$r \in \{1,2,3\}$	Final products (Rice, broken rice, and bran and husk)
$s \in \{1,...,S\}$	Suppliers
$t \in \{1,...,T\}$	Periods (year)

3.2.Parameters

YLD_{il}	The yield of rice variety *i* in region *l*
IW_{il}	Irrigation requirements of rice variety *i* in region *l*
ASW_{lt}	Available surface water in region *l* that can be dedicated to irrigation in period *t*
AGW_l	Available groundwater in region *l*
Mg_l	Groundwater mining allowance coefficient in region *l*
η_l	Irrigation efficiency in region *l*
CSW_{olt}	Cost of surface water in region *l* for land type *o* in period *t*
CGW_{olt}	Cost of groundwater in region *l* for land type *o* in period *t*
A_{lo}	Available irrigation land type *o* in region *l*
RR_{olt}	Agricultural land renting price in region *l* in period *t*(per h^2, equals 0 for owned and partnered agricultural lands)
PP_{iolt}	Cost of purchasing paddy type *i* from farmers in region *l* for land type *o* in period *t* (equals 0 for owned and rented agricultural lands)
CL_{olt}	Cost of land preparation in region *l* for land type *o* in period *t* (equals 0 for partnered agricultural lands)
CS_{olt}	Sowing cost of rice in region *l* for land type *o* in period *t* (equals 0 for partnered agricultural lands)

CH_{olt}	Harvesting cost in region *l* for land type *o* in period *t* (equals 0 for partnered agricultural lands)
SA_i	The amount of seed required for the cultivation of rice variety *i*
PS_{ist}	Purchasing cost of seed *i* from supplier *s* in period *t*
FA_{ilf}	The amount of fertilizer type *f* required for growing rice variety *i* in region *l*
PF_{fst}	Purchasing cost of fertilizer type *f* from supplier *s* in period *t*
CP_{pst}	Purchasing cost of pesticide type *p* from supplier *s* in period *t*
PA_{ilp}	The amount of pesticide type *p* required for rice variety *i* in region *l*
CLB_{olt}	Labor cost in region *l* for land type *o* in period *t* (equals 0 for partnered agricultural lands)
LC	Required labor for cultivation and harvesting of rice
TCS_{slt}	Transportation cost of rice seeds from supplier *s* to region *l* in period *t*
TCF_{slt}	Transportation cost of fertilizers from supplier *s* to region *l* in period *t*
TCP_{slt}	Transportation cost of pesticides from supplier *s* to region *l* in period *t*
TC_{lmt}	Transportation cost of paddy from region *l* to milling center *m* in period *t*
TC'_{mdt}	Transportation cost of final products from milling center *m* to distribution center *d* in period *t*
$TC''_{\det}$	Transportation cost of final products from distribution center *d* to customer *e* in period *t*
D_{iret}	The demand of customer *e* for product type *r* of rice variety *i* in period *t*
PR_{iret}	The selling price of product type *r* of rice variety *i to* customer *e* in period *t*
CAP_{rd}	The capacity of distribution center *d* for product type *r*
$CAPM_{m\neq m_2}$	The capacity of milling centers m_1 and m_3
$CAPM'_{m_2c}$	The capacity of the potential milling center m_2 with capacity level *c*
$CAPS_{ist}$	The capacity of supplier *s* for providing rice seed *i* in period *t*
$CAPF_{fst}$	The capacity of supplier *s* for providing fertilizer type *f* in period *t*
$CAPP_{pst}$	The capacity of supplier *s* for providing pesticide type *p in* period *t*
H_{irdt}	Holding cost of product type *r* of rice variety *i* in distribution center *d* in period *t*
OC_{m_2c}	Opening cost of milling center m_2 with capacity level *c*
PRO_{mt}	Processing cost at milling center *m* in period *t*
$\alpha_{r,m\neq m_2}$	The conversion ratio of paddy to final product *r* in the milling center m_1 and m_3
$dis1_{sl}$	Distance between supplier *s* and region *l*
$dis2_{lm}$	Distance between region *l* and milling center *m*
$dis3_{md}$	Distance between milling center *m* and distribution center *d*
$dis4_{de}$	Distance between distribution center *d* and customer *e*
α'_r	The conversion ratio of paddy to final product *r* in a milling center with parboiling technology
δ	Amount of CO2 emissions per km-ton
β_m	Number of laborers required per ton of product in milling center *m*
β_d	Number of laborers required per ton of product in distribution center *d*

3.3. Decision variables

SW_{lt}	Amount of surface water used for irrigation in region *l* in period *t*
GW_{lt}	Amount of groundwater used for irrigation in region *l* in period *t*
XS_{islt}	Quantity of rice seed of variety *i* transported from supplier *s* to region *l* in period *t*
XF_{fslt}	Quantity of fertilizer type *f* from supplier *s* to region *l* in period *t*
XP_{pslt}	Quantity of pesticide type *p* from supplier *s* to region *l* in period *t*
XC_{ilot}	The planting area of rice variety *i* in region *l* for land type *o* in period *t*
X_{ilmt}	Quantity of paddy type *i* transported from region *l* to milling center *m* in period *t*
X'_{irmdt}	Quantity of final product type *r* of rice variety *i* transported from milling center *m* to distribution center *d* in period *t*
$Y_{ir\det}$	Quantity of final product type *r* of rice variety *i* transported from distribution center *d* to customer zone *e* in period *t*
I_{irdt}	Inventory of product type *r* of rice variety *i* in distribution center *d* in period *t*
Z_{m_2c}	Binary variable: 1 if the milling center m_2 with capacity level *c* is opened, 0 otherwise.

3.4. Objective functions and constraints

The first objective function formulates the economic pillar in the sustainable situation and aims to maximize total profit, including Equations (1) through (12). Equation (1) is the total revenue. Equation (2) represents the cost of purchasing and transporting rice seeds. Equation (3) calculates the costs of purchasing and transporting fertilizers. Equation (4) is the pesticide transportation and purchasing costs. Equation (5) presents the paddy's transportation cost to milling centers. The total costs of transporting final products from milling centers to distribution centers are presented in Equation (6). Equation (7) calculates the transportation cost of final products from distribution centers to customers. Holding costs in distribution centers are shown in Equation (8). The processing costs of milling centers are shown in Equation (9). The Equation (10) includes renting agricultural land, purchasing paddy, land preparation, seed sowing, harvesting, and labor costs. Equation (11) presents the surface and groundwater costs. Opening costs of milling centers with parboiling technology are shown in Equation (12).

The second objective function regards the environmental pillar and aims to minimize CO2 emissions. The first three terms of Equation (13) are the emission of CO2 when transporting from suppliers to the regions. The next three terms calculate the amount of CO2 emissions transported from regions to milling centers, milling centers to distribution centers, and distribution centers to customers. Given the third objective function in (14), it aims to maximize the number of job creations in milling and distribution centers.

$$Max\ Z_1 = \sum_i \sum_r \sum_d \sum_e \sum_t PR_{iret}.Y_{ir\det} \quad (1)$$

$$-\sum_i \sum_s \sum_l \sum_t (PST_{ist} + TCS_{slt}).XS_{islt} \quad (2)$$

$$-\sum_f \sum_s \sum_l \sum_t (PF_{fst} + TCF_{slt}).XF_{fslt} \quad (3)$$

$$-\sum_p \sum_s \sum_l \sum_t (CP_{pst} + TCP_{slt}).XP_{pslt} \quad (4)$$

$$-\sum_i \sum_l \sum_m \sum_t TC_{lmt}.X_{ilmt} \quad (5)$$

$$-\sum_i \sum_r \sum_d \sum_t TC^{'}_{mdt}.X^{'}_{irmdt} \quad (6)$$

$$-\sum_i \sum_r \sum_d \sum_e \sum_t TC^{''}_{\det}.Y_{ir\det} \quad (7)$$

$$-\sum_i \sum_r \sum_d \sum_t H_{irdt}.I_{irdt} \quad (8)$$

$$-\sum_i \sum_l \sum_m \sum_t PRO_{mt}.X_{ilmt} \quad (9)$$

$$-\sum_i \sum_l \sum_o \sum_t \left[RR_{olt} + PP_{ilot} + YLD_{il} + CL_{olt} + CS_{olt} + CH_{olt} + CLB_{olt}.LC\right].XC_{ilot} \quad (10)$$

$$-\sum_l \sum_o \sum_t (CSW_{olt}.SW_{lt} + CG_{olt}.GW_{lt}) \quad (11)$$

$$-OC_{m_2c}.Z_{m_2c} \quad (12)$$

$$\begin{aligned} Min\ Z_2 =& \delta(\sum_i \sum_s \sum_l \sum_t dis1_{sl} XS_{islt} + \sum_f \sum_s \sum_l \sum_t dis1_{st} XF_{fslt} + \\ & \sum_p \sum_s \sum_l \sum_t dis1_{sl} X_{pslt} + \\ & \sum_i \sum_l \sum_m \sum_t dis2_{lm} XS_{ilmt} + \sum_i \sum_r \sum_m \sum_d \sum_t dis3_{md} X^{'}_{irmdt} \\ & + \sum_i \sum_r \sum_d \sum_e \sum_t dis4_{de} Y_{ir\det}) \end{aligned} \quad (13)$$

$$Max\ Z_3 = \sum_i \sum_l \sum_m \sum_t \beta_m X_{ilmt} + \sum_i \sum_r \sum_m \sum_d \sum_t \beta_d X^{'}_{irmdt} \quad (14)$$

St.:

$$\sum_i I_{irdt} \le CAP_{rd} \qquad \forall r,d,t \quad (15)$$

$$\sum_i \sum_l X_{ilmt} \le CAPM_m \qquad \forall m_1, m_3, t \quad (16)$$

$$\sum_i \sum_l X_{ilm_2t} \le \sum_c CAPM^{'}_{m_2c}.Z_{m_2c} \qquad \forall m_2, t \quad (17)$$

$$\sum_c Z_{m_2c} \le 1 \qquad \forall m_2 \quad (18)$$

$$\sum_d Y_{ir\det} = D_{iret} \qquad \forall i,r,e_1,t \quad (19)$$

$$\sum_d Y_{ir\det} \le D_{iret} \qquad \forall i,r,e_2,t \quad (20)$$

$$I_{ird,t-1} + \sum_m X^{'}_{irmdt} - \sum_e Y_{ir\det} - I_{irdt} = 0 \qquad \forall i,r,d,t \quad (21)$$

$$\sum_d X^{'}_{irmdt} = \sum_l \alpha_{rm} X_{ilmt} \qquad \forall i,r,m_1,m_3,t \quad (22)$$

$$\sum_d X^{'}_{irmdt} = \sum_l \alpha^{'}_r X_{ilmt} \qquad \forall i,r,m_2,t \quad (23)$$

$$\sum_i XC_{ilot} = A_{lo} \qquad \forall l,t,o \quad (24)$$

$$\sum_i XC_{ilot} = A_{lo} \qquad \forall l,t,o = owned \quad (25)$$

$$SW_{lt} \le ASW_{lt} \qquad \forall l,t \quad (26)$$

$$GW_{lt} \le Mg_l.AGW_l \qquad \forall l,t \quad (27)$$

$$\sum_i \sum_o IW_{il} XC_{ilot} - \eta(IW_{lt} + GW_{lt}) \le 0 \qquad \forall l,t \quad (28)$$

$$\sum_s XS_{islt} = SA_l.\sum_o XC_{ilot} \qquad \forall i,l,t \quad (29)$$

$$\sum_l XS_{islt} \le CAPS_{ist} \qquad \forall i,s,t \quad (30)$$

$$\sum_s XF_{fslt} = \sum_i FA_{ilf} . \sum_o XC_{ilot} \qquad \forall f,l,t \qquad (31)$$
$$\sum_l XF_{fslt} = CAPF_{fst} \qquad \forall f,s,t \qquad (32)$$
$$\sum_s XP_{pslt} = \sum_i PA_{ilp} . \sum_o XC_{ilot} \qquad \forall p,l,t \qquad (33)$$
$$\sum_l XP_{pslt} \le CAPP_{pst} \qquad \forall p,s,t \qquad (34)$$
$$YLD_{il} \sum_o XC_{ilot} = \sum_m X_{ilmt} \qquad \forall i,l,t \qquad (35)$$
$$SW_{lt}, GW_{lt}, XS_{islt}, XF_{fslt}, XP_{pslt}, XC_{ilot}, X_{ilmt}, X'_{irmdt}, Y_{ir\det}, I_{irdt} \ge 0, Z_{m_2c} \in \{0,1\} \qquad (36)$$

Constraint (15) represents the maximum available capacity of distribution centers. Constraint (16) shows the processing capacity of milling centers owned by the company as well as the capacity of independent milling centers. Constraint (17) ensures that the flows from farmlands to milling centers with parboiling technology cannot exceed the maximum capacity of the opened milling centers. Constraint (18) declares that only one capacity level can be selected in each potential location. The demand for the first group of customers should be fully satisfied, which is presented in the constraint (19). Moreover, the transported final products to other customers cannot exceed their demand, which is shown in constraint (20). The flow balance in each distribution center is calculated in constraint (21). Constraint (22) calculates the number of final products based on the conversion ratio of the company's milling centers and independent milling centers. The output of milling centers with parboiling technology is calculated in constraint (23). Constraint (24) shows the maximum available area of farmlands. All the available owned land should be cultivated which is presented in constraint (25). Maximum available surface water is presented in constraint (26). Constraint (27) guarantees that the amount of groundwater cannot exceed the available groundwater considering the mining allowance coefficient in each region. Constraint (28) calculates the planting area considering the irrigation water requirements in each region. Constraint (29) calculates the required quantity of rice seeds. The maximum capacity of each supplier for providing rice seeds is shown in constraint (30). The required quantity of fertilizers is shown in constraint (31), and the maximum capacity of each supplier for providing each fertilizer is presented in constraint (32). Constraint (33) calculates the required quantity of pesticides. The maximum capacity of each supplier for each pesticide is shown by constraint (34). The quantity of paddy transported from lands to milling centers is calculated according to the yield of rice variety, shown in constraint (35). The last constraint (36) presents the type and the domain of the decision variables.

4. Case study

We examine the Nahid Aseman Iranian company which owns agricultural lands in three regions of Gilan province: East, Center, and West, as shown in Figure 2. This company cultivates five varieties of rice, including three local (Hashemi, Kazemi, and Jamshidjou) and two high-yield types (Shiroudi and Khazar). These rice varieties differ in yield and requirements and selling price and demand. Nahid Aseman Iranian company has six customers (customer zones), differentiating in demand and selling price. The demand of customer type one must be satisfied while fulfilling others' demands is not obligatory. Information regarding demands is represented in Table 2.

As mentioned before, the company can rent farmlands in addition to owned farmlands or offer a partnership contract to independent farmers. Table 3 presents the available land area concerning farmland type. Table 4 shows the renting cost, and Table 5 presents the purchasing price of paddies in a partnership contract. Since the independent farmers perform agricultural activities in a partnership contract, the provisioning cost for cultivation, seed sowing, irrigation, and harvest is zero.

The essential requirements for cultivating crops are seeds, water, fertilizer, and pesticide. Two suppliers supply rice varieties. The yield of rice varieties in each region and the procurement prices of rice seeds from each supplier are presented in Table 6. The required seeds per hectare are about 45 kg. Each rice variety differs in irrigation water requirements depending on the cultivated regions. Table 7 presents the details of water requirements.

Fertilizers enhance the growth and yield of crops by adding additional nutrients that enrich the soil. Three types of fertilizers are procured from suppliers, including Urea, Potassium Sulfate, and Triple Super Phosphate. The needed amount, fertilizers' suppliers, and prices are presented in Tables 8 and 9. Pesticides are chemical or biological substances that are used for destroying harmful insects and organisms. The needed amount of pesticide and prices of two kinds of pesticides supplied by Agricultural Support Services Company. and Wholesalers are presented in Tables 10 and 11.

The conversion ratio of paddy to rice, broken rice, bran, and husk is 0.69, 0.01, and 0.05, respectively, in a milling center with parboiling technology. However, it is estimated to be at most 0.55, 0.15, and 0.05 using current technologies. Paddies contain up to 25% moisture and should dry within 24 hours to prevent damage and deterioration. The maximum milling centers' processing capacity is shown in Table 12. A potential milling center with parboiling technology can be opened at three capacity levels: 5000, 10000, and 15000 tones.

Final products are transported from milling centers to distribution centers. This company has three distribution centers in the Center, West, and East of Gilan province, with a maximum capacity of 6000, 3000, and 30000 tonnes. Other data, such as transportation costs dependent on inflation, are considered due to changes in inflation rates each year.

5. Solution approach

Given the multi-objective functions, a set of variables that may improve the value of one objective function can act conversely in other functions, and vice versa. Thus, a set of non-dominant solutions are considered instead of a single optimal solution, which is called the "Pareto Front". To obtain the set of solutions (Pareto Front), the ε-constraint method is implemented. n this method, one of the objective functions is considered a primary objective function, and other objective functions are considered constraints.

$$\max \ (\mathrm{f}_1(x), \mathrm{f}_2(x), \ldots, \mathrm{f}_d(x)) \tag{37}$$

s.t.

$$x \in S \tag{38}$$

The main problem is as above, which includes *d* objective functions, feasible region *S* and *x* that refer to decision variables. In the ε-constraint method, one of the objective functions is optimized and the rest are the constraints as follows:

$$\max \ f_1(x) \quad (39)$$

$s.t.$

$$f_1(x) \geq e_1 \quad (40)$$

$$f_2(x) \geq e_2 \quad (41)$$

$\dots$

$$f_d(x) \geq e_d \quad (42)$$

$$x \in S \quad (43)$$

The efficient solutions to this problem are obtained by parametrical variation of the Right-Hand Side (RHS) of constrained objective functions (e_i).

6. Computations and results

The proposed mathematical model is coded and solved in GAMS 24.7.4 on a computer with Intel® Core™ i7-6500U 2.5 GHz and 16GB DDR4 Memory, using the data presented in the previous section.

6.1. Payoff matrix

To implement ε-constraint approach, the objective functions are divided into desired ranges. A common approach to calculate the range of changes in objective functions is to use a payoff matrix. The payoff matrix is shown in Table 13.

The model is solved in twenty iterations by ε-constraint method. The Pareto front figures are presented in Figures 3, 4, 5, and 6.

Table 14. identifies the objective functions for the 10th iteration (This iteration covers about 76% of the best solution of the first objective function, 52% of the second, and 50% of the third objective function. In the following, this iteration will be used to perform some analysis.) The optimal planting area of the 10th iteration is presented in Table 15.

Table 16 presents the optimal flow of paddies from farmlands to milling centers. It is notable that owned milling centers are almost fully occupied. Also, paddies are usually processed in the farmlands. The quantity of rice products supplied for each customer is shown in Table 17. Notably, the amount of rice transported to customer 2 equals zero for periods 1 and 2. Moreover, rice variety 4 is only produced for customer 1, since fulfilling its demand is obligatory.

7. Further discussion

This section investigates the effect of changing the parameters to verify the results and determine the critical parameters whose values significantly impact the results.

7.1. Effects of changes in irrigation efficiency in the amount of surface and groundwater used in all regions

In all periods, the optimal value of irrigation efficiency in the east, west, and center of each region is equal to 0.5, 0.5, and 0.6 respectively. Thus, we solved the problem when the irrigation efficiency is increased by 10, 20, and 50 percent. The results are presented in Figure 7. Since the planting area in the first and second periods is less than in the third period, more water resource was used in the third period.

7.2.Effect of changes in the selling price of high-yield and local-yield types

Considering the significance of this parameter, we studied the economic objective function (z_1) when the selling price changes by 10% and 20%. The results are shown in Figure 8. and Figure 9. As can be seen, the rate of change in profit by changes in selling price, in the high-yield type, is greater than the local one. Because in the normal situation, high-yield cultivation is not economical.

7.3.Effects of changes in conversion ratio

This section investigates the effects of conversion ratio improvement on all objective functions. Therefore, the conversion rate is improved by 2, 5, and 8 percent. Notably, paddies contain up to 25% moisture, and the proportion of bran and husk is constant. The conversion ratio changes rate is shown in Table 18. and the effect of these changes on the objective functions is shown in Figures 10,11, and 12.

As shown in Figure 10, increasing the conversion ratio will produce more rice to increase profits. As rice production increases, the frequency of transportation will increase, so the amount of CO2 emissions will subsequently increase.

7.4. Effects of changes in agricultural land renting price

The effects of the reduction in rental cost on the planting areas in the west, east, and center of Gilan is investigated in this section. The cost is reduced by 10 and 30 percent for this aim. As shown in Figure 13, by decreasing the rental cost, the share of rented lands will increase. Also, the area of the owned land is fixed in all cases due to the condition of the problem.

7.5.Effects of reduction in the budget on the share of some cost

This sensitivity analysis was performed to observe the share of each cost in the first objective function and the effect of budget reduction on this share. The main costs considered are transportation costs, holding costs in distribution centers, opening costs of milling centers with parboiling technology, purchasing costs (including rice seeds, fertilizers, pesticides, and paddy), processing costs of milling centers, costs of surface and groundwater, rental cost and land preparation. Then, by 10 and 30 percent reduction in cost, which is considered a budget, the share of each item mentioned above is examined in Figures 14 and 15.

7.6.Effects of inflation rate

In the case study of this paper, the effects of inflation due to rising prices are evident. Therefore, we have solved the model in two cases: 1) With increases in prices in the three periods and 2) without increases in prices in these three periods. The results are shown in Figure.16, 17, and 18 for the effects of this change on the objective functions and shown in Figure 19. If prices and costs remain stable in different periods, the profit will increase further. This is shown in Figure

16. As production increases, the need for labor will increase. Thus, more job opportunities are created. These two items can be seen in Figures 17 and 18, respectively.

7.7.Managerial insights

Some managerial insights are provided in the following, which are helpful for managers and decision-makers.

- Parboiling technology can increase the chain's profit by reducing the breakage of rice and improving the value of final products. Investment in the establishment of milling centers with parboiling technology would be helpful.
- Due to the high costs of cultivation and harvest, entering a partnership agreement is much more profitable than renting farmlands. Thus, managers should focus on contract farming to improve the regulation, terms, and conditions in this regard.
- An increase in the conversion ratio of milling centers has a significant effect on total profit. Therefore, investing in new technologies for milling centers is recommended.
- Transportation costs have a significant share in the total costs. This causes air pollution and reduces profits. Replacing the worn-out fleet with a new fleet, constructing distribution, and milling centers close to farms are helpful.
- Using different irrigation technologies in rice cultivation aims to increase the efficiency of water consumption, either by reducing the amount of irrigation water or by eliminating the low-efficiency irrigation which does not significantly affect the net profit.
- It is necessary to upgrade the technology of traditional milling centers. Establishing high-capacity factories instead of smaller units reduces costs while increasing productivity.
- It would be possible to organize an integrated performance measurement system of farmers in comparison with the traditional production system.
- Designing and planning for returns should be performed considering the planned and unplanned scenarios. The first one can be planned by estimating the demand while the second one is the possible spoilage happening during the distribution.

8. Conclusion and future research opportunity

Agri-food supply chains are composed of different processes responsible for bringing food from the farm to the table. This paper proposes a mixed-integer linear programming model for designing and planning the rice supply chain in a sustainable situation. This model determines the optimal strategic and tactical decisions related to the rice supply chain. These decisions include: 1) Selecting the varieties of rice for cultivation, 2) Determining the regions and areas under cultivation (owned, rented, and through a partnership agreement), 3) Supplier selection for seeds, fertilizers, and pesticides, 4) Selecting milling centers, 5) Determining the location and capacity of new milling centers with parboiling technology, and 6) Transportation, storage, and distribution planning.

A case study of Iran farmlands is employed to show that the model is applicable to real-world problems. The ε -constraint method is applied to solve this multi-objective model. Results indicate that opening milling centers with parboiling technology is profitable for the supply chain. In the optimal solution, three 15000-tonnes milling centers are opened in the East, west, and center of Gilan. Also, A partnership agreement is much more profitable than renting farmlands due to the high costs of cultivation and harvest. For future studies, by this model presented in this paper, it is possible to consider other parts of a country with different cultivation conditions and solve this problem more widely. Considering uncertainty is recommended since it can help provide more flexible planning. Finally, investigating the parameters of the partnership agreement, the cost-plus agreement, and other agreements is recommended. Import scheduling prevents huge price fluctuations; Therefore, considering the changes in supply (volume and time) in the short term can negatively impact the distribution and consumers; Therefore, lead time and seasonal patterns of demand should be considered in planning. Additionally, focus on the contract farming can help take the advantage of the economy of scale by integrating farmlands and supply of pesticides, fertilizer, and other vital resources

References

[1] Egorov, V., Shavina, E., and Inshakov, A., "Family farm as an organization form of the agricultural industry in the concept of sourcing and purchasing management," *International Journal of Supply Chain Management*, vol. 8, no. 4, pp. 589–595, 2019.

[2] Nattassha, R., Handayati, Y., and Simatupang, T. M., "Linear and circular supply chain: SCOR framework stages, actor analysis and the illustrative case of cassava farming," *International Journal of Business and Globalization*, vol. 26, no. 1–2, pp. 3–23, 2020.

[3] Christopher, M., *Logistics & supply chain management*. Pearson UK, 2016.

[4] Ahumada, O. and Villalobos, J. R., "Application of planning models in the agri-food supply chain: A review," *European journal of Operational research*, vol. 196, no. 1, pp. 1–20, 2009.

[5] Tsolakis, N. K., Keramydas, C. A., Toka, A. K., et al., "Agrifood supply chain management: A comprehensive hierarchical decision-making framework and a critical taxonomy," *Biosystems Engineering*, vol. 120, pp. 47–64, 2014.

[6] Kusumastuti, R. D., van Donk, D. P., and Teunter, R., "Crop-related harvesting and processing planning: a review," *International Journal of Production Economics*, vol. 174, pp. 76–92, 2016.

[7] Biswas, A. and Pal, B. B., "Application of fuzzy goal programming technique to land use planning in agricultural system," *Omega*, vol. 33, no. 5, pp. 391–398, 2005.

[8] Higgins, A. J. and Laredo, L. A., "Improving harvesting and transport planning within a sugar value chain," *Journal of the Operational Research Society*, vol. 57, no. 4, pp. 367–376, 2006.

[9] Lodree Jr, E. J. and Uzochukwu, B. M., "Production planning for a deteriorating item with stochastic demand and consumer choice," *International Journal of Production Economics*, vol. 116, no. 2, pp. 219–232, 2008.

[10] Piewthongngam, K., Pathumnakul, S., and Setthanan, K., "Application of crop growth simulation and mathematical modeling to supply chain management in the Thai sugar industry," *Agricultural Systems*, vol. 102, no. 1, pp. 58–66, 2009, doi: https://doi.org/10.1016/j.agsy.2009.07.002.

[11] Shiun, L. J., Hashim, H., Manan, Z. A., et al., "Optimal design of a rice mill utility system with rice husk logistic network," *Industrial & Engineering Chemistry Research*, vol. 51, no. 1, pp. 362–373, 2011.

[12] An, K. and Ouyang, Y., "Robust grain supply chain design considering post-harvest loss and harvest timing equilibrium," *Transportation Research Part E: Logistics and Transportation Review*, vol. 88, pp. 110–128, 2016.

[13] Bala, B. K., Bhuiyan, M. G. K., Alam, M. M., et al., “Modelling of supply chain of rice in Bangladesh,” *International Journal of Systems Science: Operations & Logistics*, vol. 4, no. 2, pp. 181–197, Apr. 2017, doi: 10.1080/23302674.2016.1179813.

[14] Ahumada, O. and Villalobos, J. R., “Decision support models for fresh fruits and vegetables supply chain management,” in *Sustainable Food Supply Chains*, Elsevier, 2019, pp. 317–337.

[15] Cheraghalipour, A., Paydar, M. M., and Hajiaghaei-Keshteli, M., “Designing and solving a bi-level model for rice supply chain using the evolutionary algorithms,” *Computers and Electronics in Agriculture*, vol. 162, pp. 651–668, 2019.

[16] Carbajal, E., Rivera, J., Ramos, E., et al., “Strategic sourcing toward a sustainable organic coffee supply chain: a research applied in Cuzco,” in *International Conference on Human Systems Engineering and Design: Future Trends and Applications*, Springer, 2019, pp. 929–935.

[17] Jifroudi, S., Teimoury, E., and Barzinpour, F., “Designing and planning a rice supply chain: a case study for Iran farmlands,” *Decision Science Letters*, vol. 9, no. 2, pp. 163–180, 2020.

[18] Pourmohammadi, F., Teimoury, E., and Gholamian, M. R., “A fuzzy chance-constrained programming model for integrated planning of the wheat supply chain considering wheat quality and sleep period: a case study,” *Scientia Iranica*, 2020.

[19] Yan, B., Liu, G., Wu, X., et al., “Decision-making on the supply chain of fresh agricultural products with two-period price and option contract,” *Asia-Pacific Journal of Operational Research*, vol. 38, no. 01, p. 2050038, 2021.

[20] Phan, L. T. K., Tran, T. M., Audenaert, K., et al., “Contamination of Fusarium proliferatum and Aspergillus flavus in the rice chain linked to crop seasons, cultivation regions, and traditional agricultural practices in mekong delta, vietnam,” *Foods*, vol. 10, no. 9, p. 2064, 2021.

[21] Chen, H., Chen, Z., Lin, F., et al., “Effective management for blockchain-based agri-food supply chains using deep reinforcement learning,” *IEeE Access*, vol. 9, pp. 36008–36018, 2021.

[22] Putro, P., Purwaningsih, E. K., Sensuse, D. I., et al., “Model and implementation of rice supply chain management: A literature review,” *Procedia Computer Science*, vol. 197, pp. 453–460, 2022.

[23] Wang, J., Zhang, X., Xu, J., et al., “Blockchain-Based Information Supervision Model for Rice Supply Chains,” *Computational Intelligence and Neuroscience*, vol. 2022, p. 2914571, Mar. 2022, doi: 10.1155/2022/2914571.

[24] Elyasi, A. and Teimoury, E., “Applying Critical Systems Practice meta-methodology to improve sustainability in the rice supply chain of Iran,” *Sustainable Production and Consumption*, vol. 35, pp. 453–468, Jan. 2023, doi: 10.1016/j.spc.2022.11.024.

[25] International Grains Council, “International Grains Council,” 2020. [Online]. Available: https://www.world-grain.com/articles/12752-focus-on-iran

Seyyed Aziz Seyyed Jifroudi is a Ph.D. candidate at the Industrial Engineering faculty, at Iran University of Science and Technology, Iran. His thesis concerns sustainable rice supply chain network design and planning. He also holds an MSc in industrial engineering and his research field includes the supply chain, transportation, and innovation. He is also a practitioner in these fields.

Ebrahim Teimoury is a Professor of Industrial Engineering at the Iran University of Science and Technology. He received his Ph.D. from the Iran University of Science and Technology in 2000 and initiated his work as a faculty member at SIE in 2001. His research vision is concentrated mainly on Supply Chain Management. He teaches Supply Chain Management, E-supply Chain Management, Socio-economic Systems Modeling, Systems Engineering, Queuing Theory, Probability Theory, and Mathematical Statistics. He is the author (or co-author) of more than 100 scientific papers and a referee for more than five international scientific journals

Dr. Farnaz Barzinpour is an Associate Professor at the School of Industrial Engineering at the Iran University of Science and Technology (IUST), Tehran, Iran. She received her Ph.D. from Tarbiat Modares University in 2004, Tehran, Iran. She initiated her work as a faculty member in 2005. She has published and presented more than 170 papers in many national and international journals and conferences. Her research interests include optimization and meta-heuristic algorithms, supply chain management, and health systems

List of Figures:

Figure 5- Pareto optimal solutions (economic vs. environmental)

Figure 6- Pareto optimal solutions (environmental vs. social)

Figure 7- Effects of the irrigation on water used

Figure 8- Effects of change in the selling price with a 10% increase

Figure 9- Effects of changes in the selling price with a 20% increase

Figure 10- Effects of improvement in conversion ratio on the economic objective

Figure 11- Effects of improvement in conversion ratio on the environmental objective

Figure 12- Effects of improvement in conversion ratio on the social objective

Figure 13- Effects of decrease in agricultural rental cost on the optimal planting area (ha)

Figure 14- Effects of 10% decrease in the budget on the share of costs

Figure 15- Effects of 30% decrease in the budget on the share of costs

Figure 16- Effects of inflation on the economic impact

Figure 17- Effects of inflation on the environmental impact

Figure 18- Effects of inflation on the social impact

Figure 19- Effects of inflation on the planting areas

Table 1

Reference	**Decisions**								**Model characteristics**								**Case study**	**Solution Approach**
	Cropping pattern	Agricultural tasks Scheduling	Harvest scheduling	Milling center location	Inputs Supplier Selection	Irrigation Water Allocation	Inventory planning	Distribution	Single-objective	Multi-objective	Single-period	Multi-period	Linear	Non-linear	Deterministic	Uncertain		
Biswas and Pal (2005)	*				*					*		*	*			*		E
Higgins and Laredo (2006)			*					*		*	*			*	*		*	H
Lodree Jr and Uzochukwu (2008)							*		*			*		*		*		E
Piewthongngam et al. (2009)	*	*	*						*			*	*		*		*	H
Shiun et al. (2011)				*					*			*	*		*		*	E
An and Ouyang (2016)		*	*					*		*				*		*	*	GT
Cheraghalipour et al. (2019)	*			*				*	*			*		*	*			MH
Jifroudi et al.	*****				*****	*****	*****	*****	*****		*****		*****		*****		*****	**E**

Table 1

Reference	Decisions								Model characteristics								Case study	Solution Approach
	Cropping pattern	Agricultural tasks Scheduling	Harvest scheduling	Milling center location	Inputs Supplier Selection	Irrigation Water Allocation	Inventory planning	Distribution	Single-objective	Multi-objective	Single-period	Multi-period	Linear	Non-linear	Deterministic	Uncertain		
(2020)																		
Chen et al.(2021)							*	*	*				*				*	**MH**
Wang et al., (2022)															*			**H**
This paper	*			*	*	*	*	*		*		*	*		*		*	**E**

E: Exact, H: heuristic, MH: Meta-heuristic GT: Game Theory.

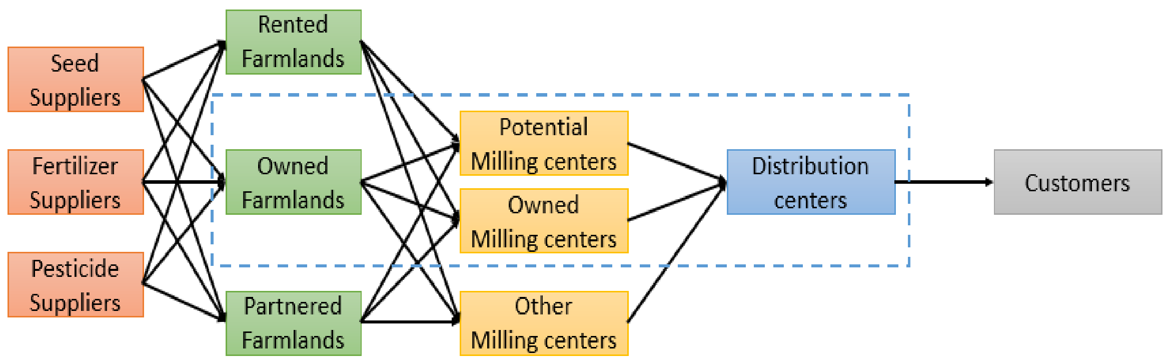

Figure 3

Figure 4

Table 2

Rice variety	Product/Customer	1	2	3	4	5	6
1	Rice	0	0	5000	10000	10000	0
	Broken rice	0	0	0	0	0	100000
	Bran and husk	0	0	0	0	0	100000
2	Rice	0	0	1000	10000	10000	0
	Broken rice	0	0	0	0	0	100000
	Bran and husk	0	0	0	0	0	100000
3	Rice	0	0	0	0	10000	0
	Broken rice	0	0	0	0	0	100000
	Bran and husk	0	0	0	0	0	100000
4	Rice	5000	5000	5000	1000	30000	0
	Broken rice	0	0	0	0	0	100000
	Bran and husk	0	0	0	0	0	100000
5	Rice	20000	25000	10000	2000	50000	0
	Broken rice	0	0	0	0	0	100000
	Bran and husk	0	0	0	0	0	100000

Table 3

Province	Regions	Land type		
		Owned	**Available for rent**	**Available for a partnership contract**
Gilan	East	1000	1200	20000
	Center	500	200	30000
	West	5000	700	20000

Table 4

Province	Regions	Period (Year)		
		1	**2**	**3**
Gilan	East	894	938	987
	Center	983	1037	1096
	West	894	938	987

Table 5

Rice variety	Regions	Period (Year)		
		1	**2**	**3**
1	East	357	375	395
	Center	357	375	395
	West	357	375	395
2	East	272	286	301
	Center	272	286	301
	West	272	286	301
3	East	290	350	368
	Center	290	350	368
	West	290	350	368
4	East	214	271	285
	Center	214	271	285
	West	214	271	285
5	East	201	212	269
	Center	201	212	269
	West	201	212	269

Table 6

Rice variety	Price (Iranian Rial)		The yield of rice variety		
	Local suppliers	**Agricultural Support Services Co.**	**Center**	**West**	**East**
1	80000	100000	4	4	4
2	70000	90000	4	4	4
3	65000	80000	4	4	4
4	65000	75000	6.5	6.5	6.5
5	63000	70000	6.5	6.5	6.5

Table 7

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

Table 8

Fertilizers	**Urea**			**Potassium Sulfate**			**Triple Super Phosphate**		
Region/ Rice variety	**West**	**Center**	**East**	**West**	**Center**	**East**	**West**	**Center**	**East**
1	90	100	95	150	150	150	100	90	80
2	80	95	85	140	140	140	100	90	80
3	80	95	85	130	140	140	100	90	80
4	150	140	145	300	250	250	100	150	90
5	150	140	145	300	250	250	100	150	90

Table 9

Fertilizer/Supplier	**Agricultural Support Services Company**			**Wholesalers**		
	Period 1	**Period 2**	**Period 3**	**Period 1**	**Period 2**	**Period 3**
Urea	38444	42289	46518	38444	42289	46518
Potassium Sulfate	50067	55074	60581	50067	55074	60581
Triple Super Phosphate	67054	73759	81135	67054	73759	81135

Table 10

Pesticides	**1**			**2**		
Region/ Rice variety	**West**	**Center**	**East**	**West**	**Center**	**East**
1,2,3	1	1	1	0.5	0.5	0.5
4,5	1.3	1.3	1.3	0.75	0.75	0.75

Table 11

Suppliers:	**Agricultural Support Services Co.**			**Wholesalers**		
Pesticides	**Period 1**	**Period 2**	**Period 3**	**Period 1**	**Period 2**	**Period 3**
1	8717032	9588735	10547608	8717032	9588735	10547608
2	15198927	16718820	18390702	15198927	16718820	18390702

Table 12

Owned milling centers		**Other milling centers**	
Region	**Capacity**	**Region**	**Capacity**
Center of Gilan	8000	Center of Gilan	335900
West of Gilan	2500	West of Gilan	360460
East of Gilan	12000	East of Gilan	462120

Table 13

	Z_1	Z_2	Z_3
$max\ Z_1$	1.06×10^{10}	2.95×10^{8}	271282
$min\ Z_2$	4.63×10^{8}	2.70×10^{7}	28455
$max\ Z_3$	9.64×10^{9}	3.18×10^{8}	287238

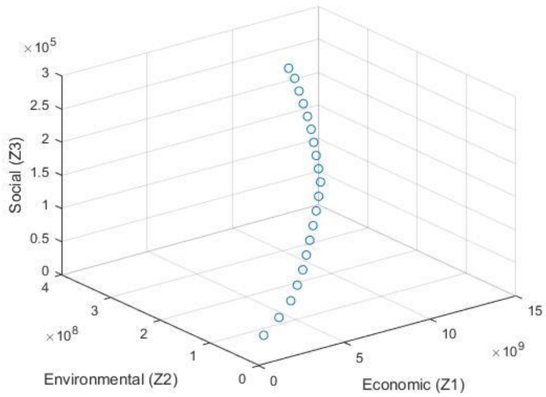

Figure 3

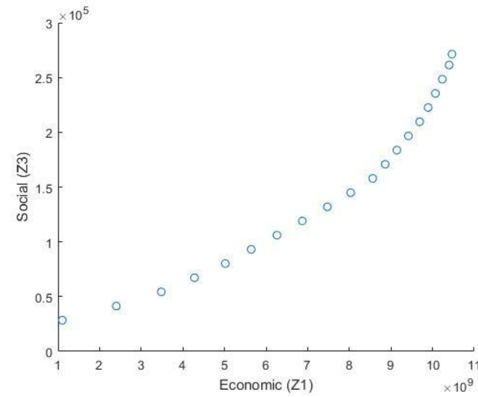

Figure 4

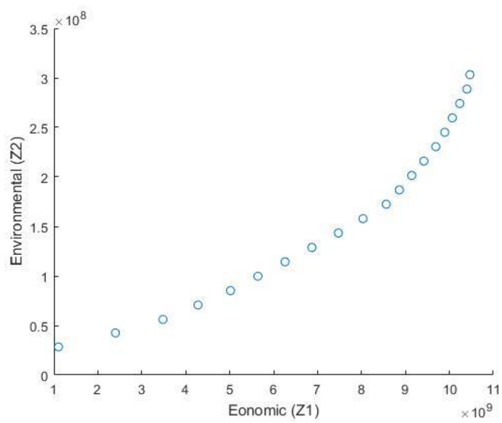

Figure 5

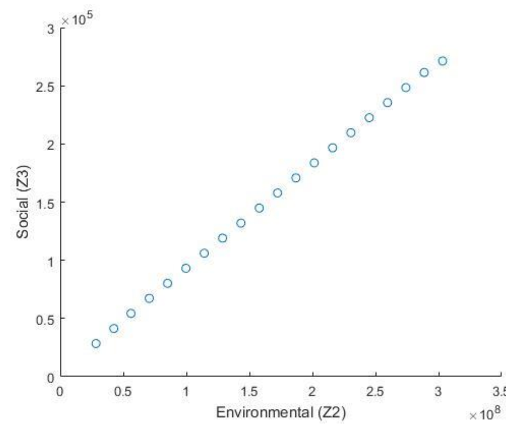

Figure 6

Table 14

	Z_1	Z_2	Z_3
Optimal objective functions of iteration 10	8.03×10^{9}	1.58×10^{8}	144907.1

Table 15

Rice variety	Owned			Partnership agreement			Rented	Total planting	Rice variety's share (%)
	Center	West	East	Center	West	East			

									area	
		Period 1								
Local	**1**	1000	500	5000	0	0	0	0	6500	18.8%
	2	0	0	0	0	7376.0	1181.8	0	8557.8	24.8%
	3	0	0	0	4048.7	5409.1	4500	0	13957.8	40.4%
High-yield	**4**	0	0	0	1098.9	0	0	0	1098.9	3.2%
	5	0	0	0	1297.6	2307.7	790.3	0	4395.6	12.7%
Total area		1000	500	5000	6445.2	15092.8	6472.1	0	34510.1	-
		Period 2								
Local	**1**	1000	500	3846.2	0	2967.7	7697.6	0	16011.5	52.3%
	2	0	0	0	0	0	8840.9	0	8840.9	28.9%
	3	0	0	0	0	0	0	0	0	0.0%
High-yield	**4**	0	0	1153.8	0	0	0	0	1153.8	3.8%
	5	0	0	0	0	1153.8	3461.5	0	4615.3	15.1%
Total area		1000	500	5000	0	4121.5	20000	0	30621.5	-
		Period 3								
Local	**1**	0	0	0	123.1	1013.3	0	0	1136.4	1.9%
	2	0	0	0	0	10500	0	0	10500	17.9%
	3	0	0	0	0	0	0	0	0	0.0%
High-yield	**4**	1000	500	5000	6953.8	0	0	700	14153.8	24.1%
	5	0	0	0	12923	0	20000	0	32923	56.1%
Total area		1000	500	5000	19999.9	11513.3	20000	700	58713.2	-

Table 16

		Owned milling centers			**New milling centers**			**Other milling centers**		
Regions		**Center**	**West**	**East**	**Center**	**West**	**East**	**Center**	**West**	**East**
		Period 1								
Farmlands	**Center**	8000	0	0	15000	0	9863.262	2909.091	0	0
	West	0	2500	0	0	15000	0	0	50640.494	0
	East	0	0	12000	0	0	5136.738	0	0	30727.273
		Period 2								
	Center	4000	0	0	0	0	0	0	0	0
	West	0	2500	0	0	15000	0	0	3870.629	0
	East	0	0	12000	15000	0	15000	0	0	69538.461
		Period 3								
	Center	8000	0	0	0	0	492.308	127700	0	0
	West	0	2500	0	0	0	0	0	46803.147	0
	East	0	0	12000	0	0	0	0	0	109050

Table 17

Product	**Customers**						**Total**
	1	**2**	**3**	**4**	**5**	**6**	
	Period 1						
Rice	25000	0	1000	5227.271	20000	0	51227.3
Broken rice	0	0	0	0	0	16016.5	16016.5
Bran and Husk	0	0	0	0	0	7588.8	7588.8
	Period 2						
Rice	26250	0	6300	21000	31500	0	85050
Broken rice	0	0	0	0	0	13786.4	13786.4
Bran and Husk	0	0	0	0	0	6845.4	6845.4
	Period 3						
Rice	27500	33000	23100	25300	121000	0	229900
Broken rice	0	0	0	0	0	52881.8	52881.8

Bran and Husk	0	0	0	0	0	17627.3	17627.3

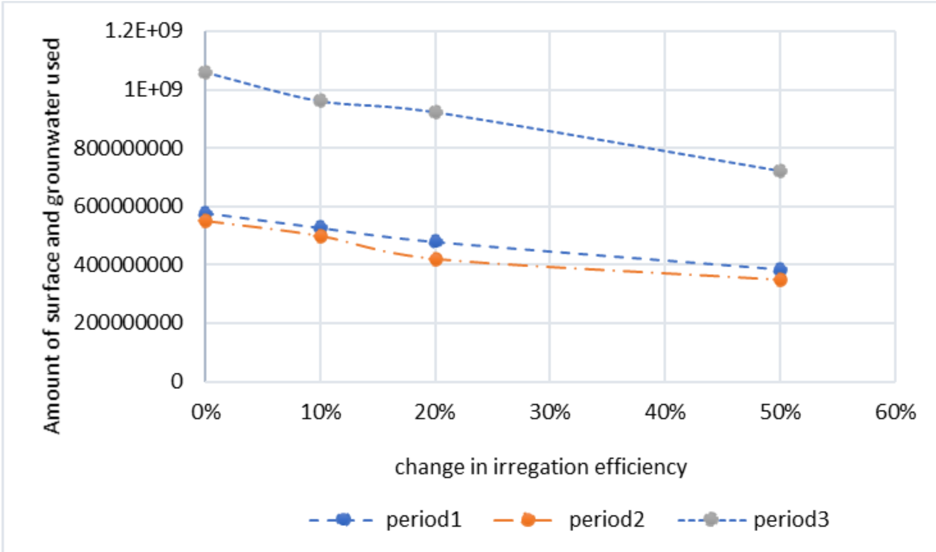

Figure 7

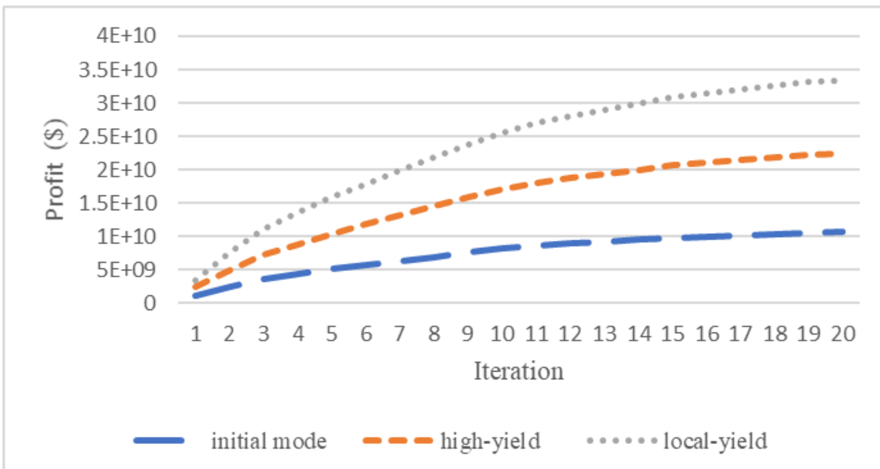

Figure 8

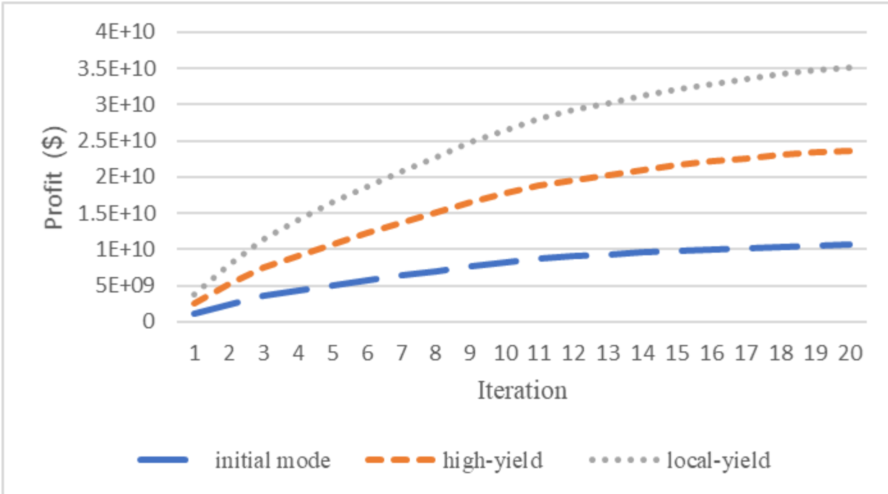

Figure 9

Table 18

Final products	**Conversion ratio**			
	No change	**2% improvement**	**5% improvement**	**8% improvement**
Rice	0.55	0.564	0.585	0.606
Broken rice	0.15	0.136	0.115	0.094
Bran and husk	0.05	0.05	0.05	0.05

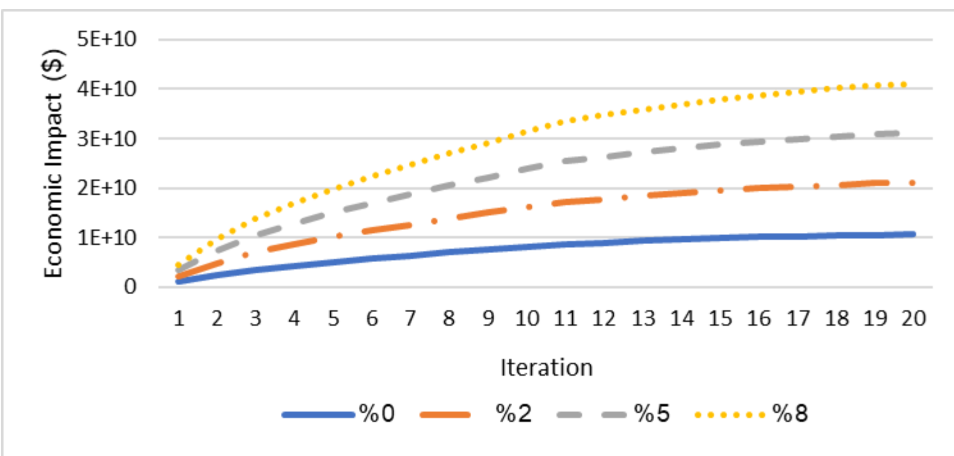

Figure 10

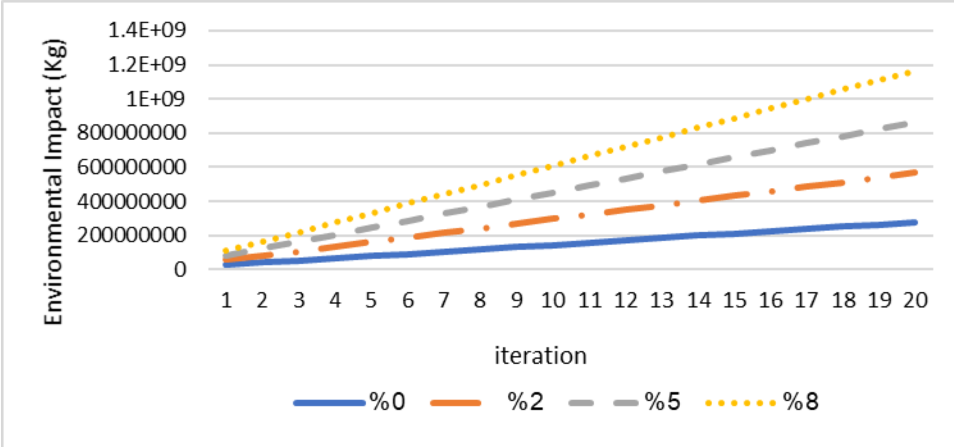

Figure 11

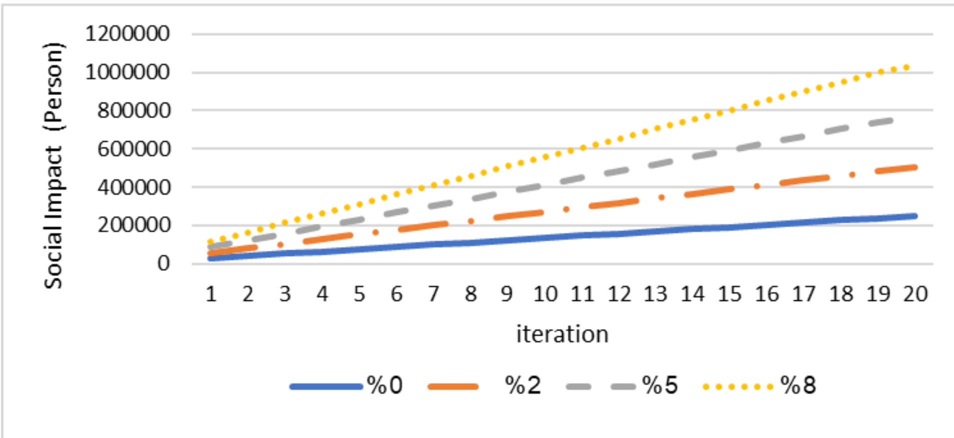

Figure 12

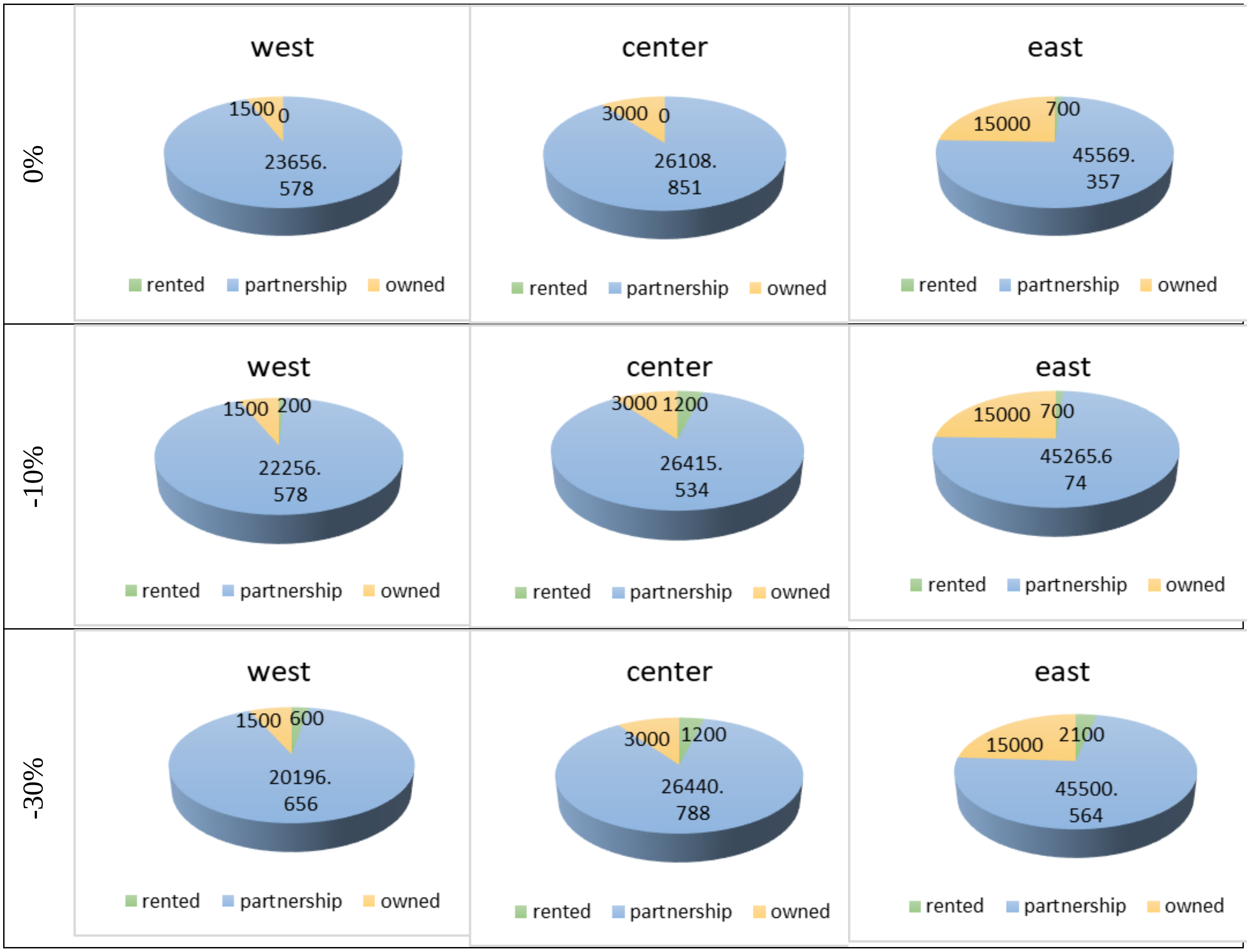
0%
west
1500
0
23656.
578
rented
partnership
owned
center
3000
0
26108.
851
rented
partnership
owned
east
15000
700
45569.
357
rented
partnership
owned
-10%
west
1500
200
22256.
578
rented
partnership
owned
center
3000
1200
26415.
534
rented
partnership
owned
east
15000
700
45265.6
74
rented
partnership
owned
-30%
west
1500
600
20196.
656
rented
partnership
owned
center
3000
1200
26440.
788
rented
partnership
owned
east
15000
2100
45500.
564
rented
partnership
owned

Figure 13

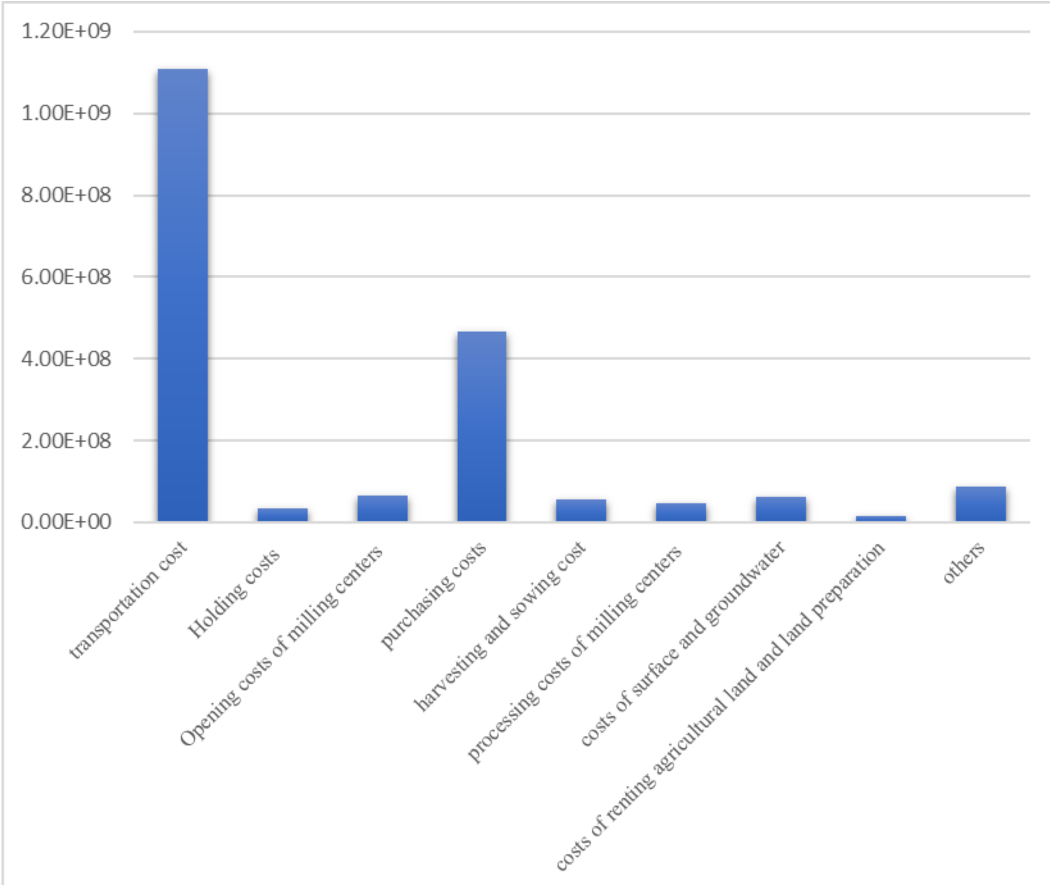

Figure 14

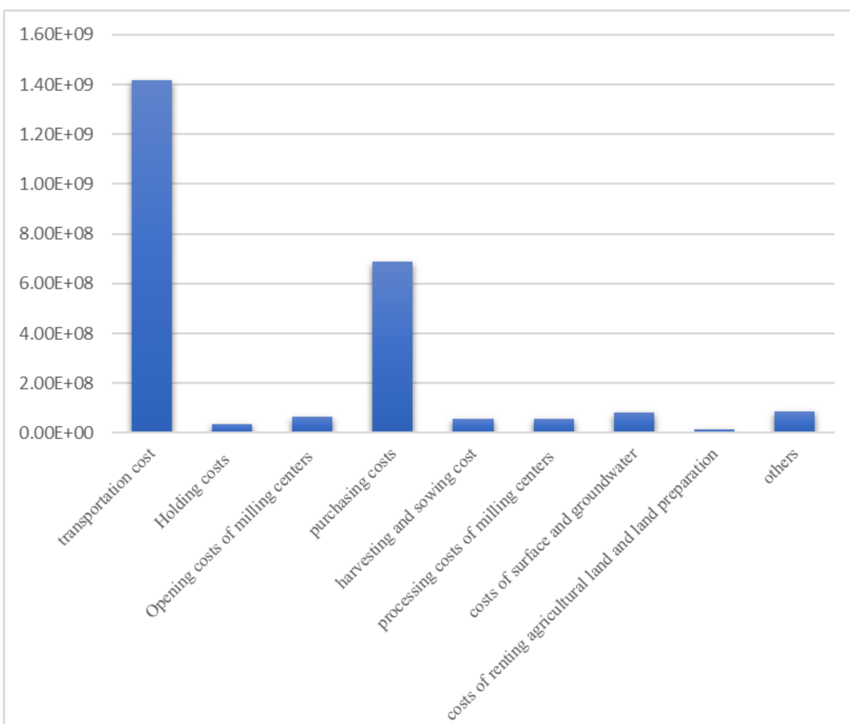

Figure 15

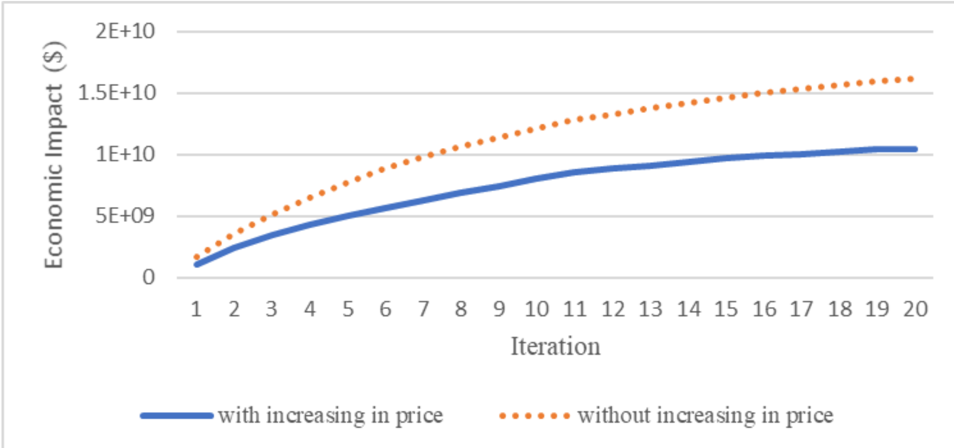

Figure 16

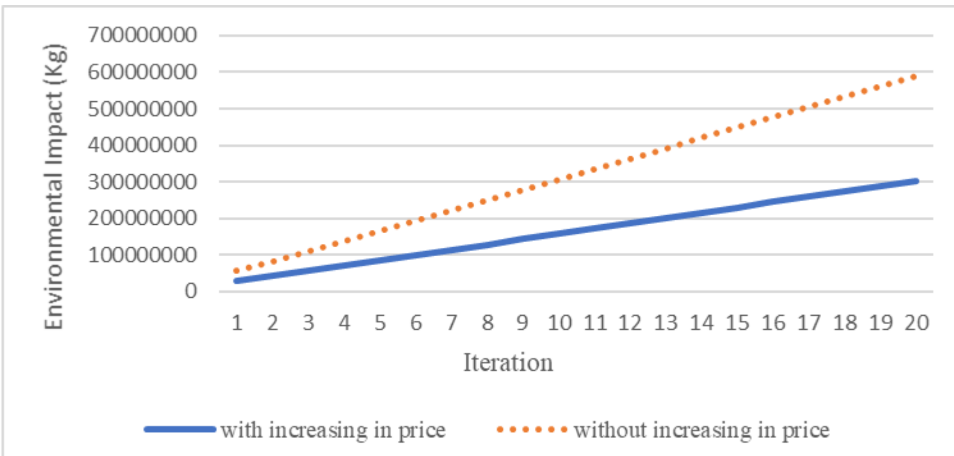

Figure 17

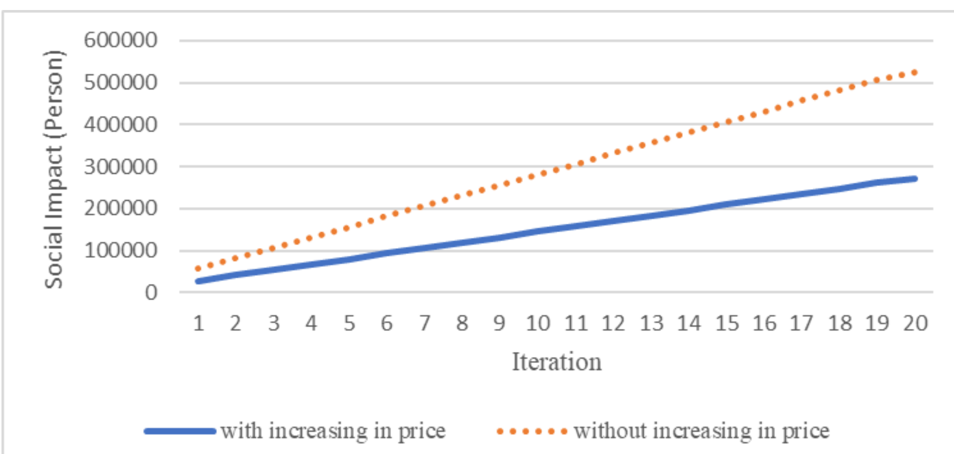

Figure 18

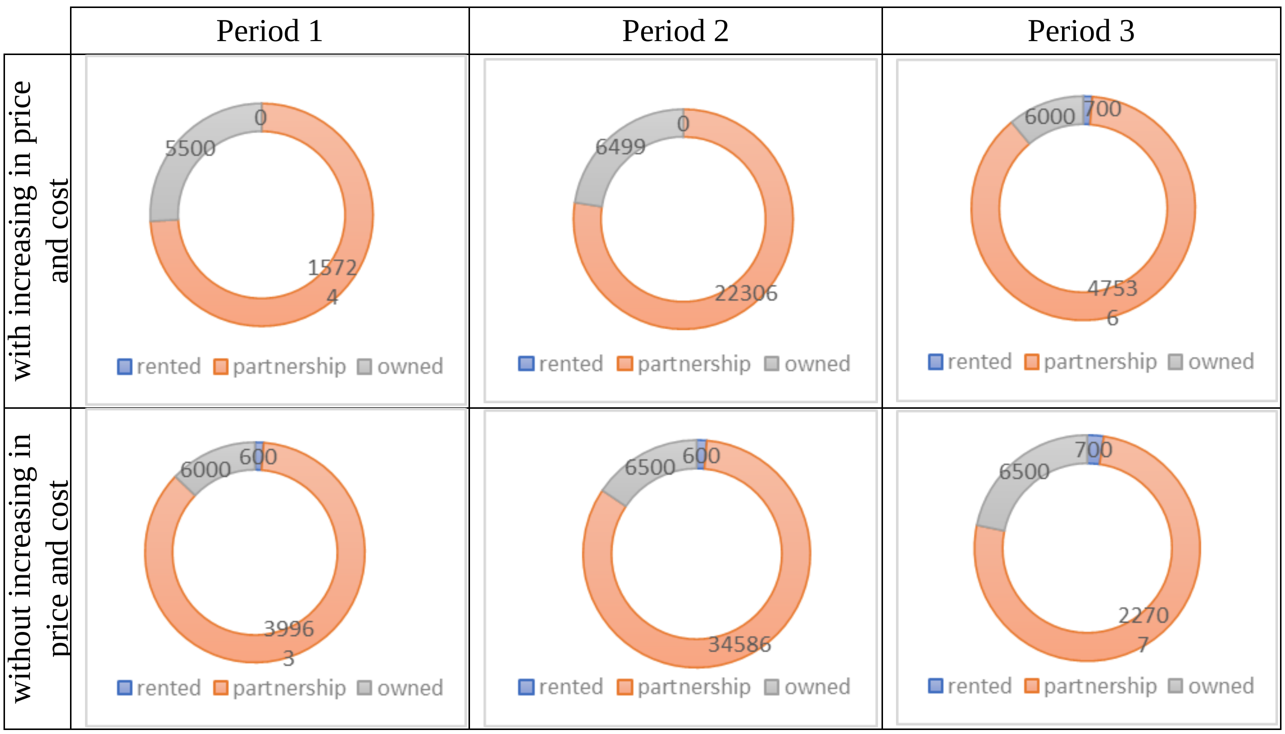
Period 1
Period 2
Period 3
with increasing in price and cost
without increasing in price and cost
0
5500
15724
rented
partnership
owned
0
6499
22306
6000
700
47536
600
6000
39963
6500
600
34586
700
6500
22707

Figure 19