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Harvest optimization for sustainable agriculture: The case of tea harvest scheduling

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ABSTRACT

To ensure sustainability in agriculture, many optimization problems need to be solved. An important one of them is harvest scheduling problem. In this study, the harvest scheduling problem for the tea is discussed. The tea harvest problem includes the creating a harvest schedule by considering the farmers' quotas under the purchase location and factory capacity. Tea harvesting is carried out in cooperation with the farmer - factory. Factory management is interested in using its resources. So, the factory capacity, purchase location capacities and number of expeditions should be considered during the harvesting process. When the farmer's side is examined, it is seen that the real professions of farmers are different. On harvest days, farmers often cannot attend to their primary professions. Considering the harvest day preferences of farmers in creating the harvest schedule are of great importance for sustainability in agriculture. Two different mathematical models are proposed to solve this problem. The first model minimizes the number of weekly expeditions of factory vehicles within the factor and purchase location capacity restrictions. The second model minimizes the number of expeditions and aims to comply with the preferences of the farmers as much as possible. A sample application was performed in a region with 12 purchase locations, 988 farmers, and 3392 decares of tea fields. The results show that the compliance rate of farmers to harvesting preferences could be increased from 52% to 97%, and this situation did not affect the number of expeditions of the factory. This result shows that considering the farmers' preferences on the harvest day will have no negative impact on the factory. On the contrary, it was concluded that this situation increases sustainability and encouragement in agriculture. Furthermore, the results show that models are effective for solving the problem.

1. Introduction

Organizing activities in the agricultural sector are the activities carried out to develop the decision-making mechanism of the producers directed towards the same purpose. The sustainable conduct of these organizational activities increases social and economic efficiency (Karlı et al., 2018). Andrei et al. (2020) argued that agricultural export competitiveness can only be achieved with increasing productivity. They mentioned that one of the elements that increase this productivity is policies aiming to expand relations in the agricultural sector. For these reasons, social optimization studies to be applied in agriculture are valuable.

Many plant species can be considered in the social optimization studies to be applied in the agricultural sector. These plant species vary according to region. Considering the Black Sea Region in Turkey, it is seen that social optimization studies can be carried out for agricultural products such as tea, hazelnuts, corn, and kiwi. When the tea production is examined, it is noteworthy that Turkey ranks seventh in the world regarding the width of tea agricultural areas and fifth in dry tea production. Turkey is located in first place according to the world's statistics of tea consumption per capita (Çaykur, 2019). For these reasons, the importance of tea in the Turkish agricultural sector is quite significant. Harvest scheduling, vehicle routing, and personnel scheduling problems in tea farming can be discussed. Optimization work can be performed for many objectives, such as complying with the farmers' preferences, minimizing the number of expeditions to purchase locations, collecting the tea harvested with the shortest route, and scheduling drivers.

The production journey of tea, which is harvested three times a year, starts with the tea collection process of the farmer. Farmers usually enter the tea field at sunrise and harvest the tea until the afternoon. The tea is transported to the so-called purchase location for the sale process of the farmer-factory. Tea is weighed, and the sales process is completed in the purchase locations. The purchase location and factory capacity constraints are important in the harvesting process. The

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intensities in the purchase locations may cause the tea to remain in the sun instead of in shaded areas. Tea can be affected by the sun. If the tea is sunburnt, it is not accepted by the factory. This causes the tea to be waste. Considering the purchase location capacity is essential to eliminate such grievances. The aim of the minimization of truck expeditions during harvest scheduling is significant to use the resources of the factories efficiently. In addition, it is important for social development and incentive to agriculture to consider the harvest day preferences in the creation of the harvest schedule. Considering these parameters in the harvest process increases national efficiency in tea farming.

In this study, the tea harvest scheduling problem is discussed. Mathematical models have been proposed for farmers and factories. These models consider the weekly harvest day preference constraints, location constraints, the purchase location capacity, and the factory capacity constraints. These problem-specific models offer an innovative approach to the tea harvesting process and contribute to the literature on harvest optimization. Most of the tea production in Turkey takes place in Rize (Çaykur, 2019). Exemplary applications have been carried out in a region with 988 farmers, 3392 decares of tea fields, and 12 purchase locations in Rize. With these applications, the performances of the recommended models were evaluated. This study is a new starting point in the literature, as it is the first work that deals with tea harvesting with the unique constraints mentioned.

The plan of the study is as follows: In the second section, the harvest scheduling problem is mentioned. In the third section, the studies in the literature are examined. In the fourth section, a sample application was performed. The result of the study is in the fifth section.

2. Harvest scheduling problem

In the production and service sectors, schedule problems are frequently encountered. The solution to these problems includes allocating certain resources to certain tasks. During the allocation, many problem-specific criteria can be found (Ceylan et al., 2019). Some issues examined in the scheduling studies are as follows: personnel scheduling (Eren and Ünal, 2016; Varlı and Tamer, 2017), job scheduling (Fanjul-Peyro et al., 2019; Lei et al., 2021; Lei and Liu, 2020), syllabus scheduling (Çolak and Yiğit, 2021; Eren et al., 2018; Yurtsal and Kaynar, 2022), maintenance scheduling(Cullum et al., 2018; Dündar and Sarıçiçek, 2021; Özcan et al., 2020). Some of the methods used are as follows: Goal programming (Ceylan et al., 2019; Eren and Ünal, 2016), artificial bee colony (Lei et al., 2021; Lei and Liu, 2020), genetic algorithm (Yurtsal and Kaynar, 2022), particle swarm optimization(Yurtsal and Kaynar, 2022).

Harvest optimization problems are the problems that are interested in finding the answers to the following questions: i. Which plant should be planted? ii. When should the harvest be done? iii. Which machines should be used? iv. Which system or which route should be taken? v. In which field should the product be planted? vi. What should be the size of the labor force to carry out the harvest? The location of harvest scheduling problems in the harvest optimization literature is shown in Fig. 1.

Harvest scheduling applications contain objectives such as efficient use of resources and maximizing the amount of harvest. With these applications, factory resources can be used more efficiently. In addition, considering the preferences of farmers can encourage communities to agriculture. In today's world, where agriculture is increasing day by day (Kirmikil and Ertaş, 2020), these studies that can increase the efficiency of both farmers and factories are important. Some harvesting processes are implemented in cooperation with farmers and factories. In these processes, both sides have benefit value. The benefit values are optimized by using resources efficiently within the problem's constraints. The optimization can only take into account farmers or factories. In addition, optimization studies that are interested in both can be carried out. These studies are handled to increase sustainability in agriculture.

3. Literature review

Harvest optimization in the literature is referred to by various names: Planting decision optimization (Rollan et al., 2018; Sajid and Hu, 2022), harvest scheduling (Thuankaewsing et al., 2011), scheduling of the machines to be used in harvesting (Edwards et al., 2015; He et al., 2018a, 2018b), labor optimization in agriculture (Busato and Berruto, 2016). Studies have different qualities regarding plant species, the objective of optimization, and the methods used. The examination of the studies according to these qualifications is shown in Table 1.

When the subjects of the literature studies given in Table 1 are examined, harvest optimization was performed for many objective, such as planting time optimization (Sajid and Hu, 2022), plant species selection optimization (Poltroniere et al., 2021), agricultural machine scheduling and routing (He et al., 2018a). Sarımehmet et al. has done one of the most recent studies on tea harvest optimization (Sarımehmet et al., 2023). The GP model is developed in the study and a real case study realized in Turkey. There was no study that optimizes the gains of farmers and factories for sustainable agriculture by taking the preferences of the farmers. Our study contributes to the literature in this respect.

It is seen that the mathematical programming method is frequently used in harvest optimization studies (Grunow et al., 2007; He et al., 2018b; Poltroniere et al., 2021; Rollan et al., 2018), Artificial neural networks (Sajid and Hu, 2022), the tabu search method (He et al., 2018a) and statistical methods (Badi et al., 2004) are also used. In this study, mathematical programming, which is the most preferred method in the literature, is used.

Fig. 2 depicts the distribution of the studies according to the plant species discussed. The most discussed plants in the literature appear to be sugar cane (Grunow et al., 2007; Poltroniere et al., 2021; Thuankaewsing et al., 2011) and rice (Busato and Berruto, 2016; He et al., 2018b) respectively. Afforestation (Rollan et al., 2018), wheat (He et al., 2018a), and thyme (Badi et al., 2004) are also available for harvest optimization. According to the literature research, tea harvesting scheduling has not been handled before. In this respect, our study fills the gap in the harvest optimization literature. Harvest optimization is discussed in the literature for many plant species for different

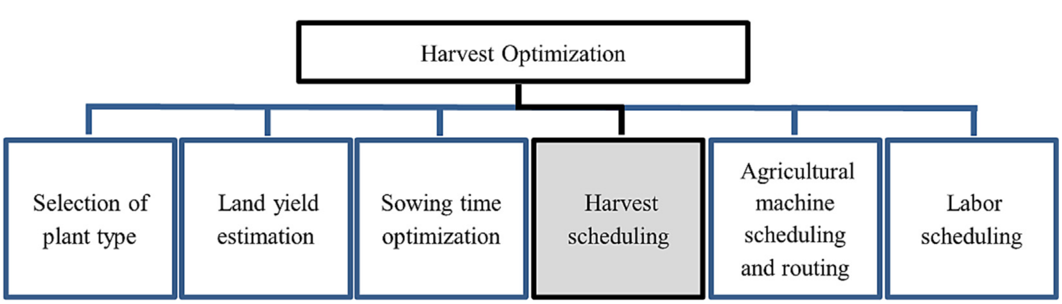


Fig. 1. The location of harvest scheduling problems in the harvest optimization literature.

Table 1
Harvest optimization literature review.

Author(s)	Plant	Problem	Method
(Sarımehmet et al., 2023)	Tea	Tea harvest scheduling	GP
(Sajid and Hu, 2022)	–	Planting time optimization	ANN, MP
(Poltroniere et al., 2021)	Sugar cane	The optimization of plant species selection	MP
(Rollan et al., 2018)	Afforestation	The optimization of plant species selection	GP
(He et al., 2018a)	Wheat	Agricultural machine scheduling	TS
(He et al., 2018b)	Rice	Agricultural machine routing	MP
(Busato and Berruto, 2016)	Rice	Labor optimization	S
(Edwards et al., 2015)	–	Agricultural machine scheduling	TS
(Thuankaewsing et al., 2011)	Sugar cane	Land yield estimation and harvest scheduling	ANN, MP
(Grunow et al., 2007)	Sugar cane	Breeding and harvest optimization	MP
(Badi et al., 2004)	Thyme	The effect of harvest time on yield	SM
(Salassi et al., 2002)	Sugar cane	Selection of harvest system	MP
(Higgins et al., 1998)	Sugar cane	Revenue optimization according to harvest time and harvest age	MP
(Astika et al., 1997)	Sugar cane	Planting and harvesting time optimization	MP
This study	*Tea*	*Harvest scheduling*	*GP*

MP: Mathematical Programming, ANN: Artificial Neural Network, TS: Tabu Search, S: Simulation, SM: Statistical Methods, GP: Goal Programming.

objective. The contributions of harvest optimization in this study to the literature are as follows:

- A Mathematical model has been developed that optimize the benefit values of the factories (the number of expeditions of the factory vehicles) in the tea harvest scheduling problem.
- A Mathematical model has been developed that optimize the benefit values of the farmers (harvesting day preferences) in the tea harvest scheduling problem.
- In mathematical models developed, there are problem-specific constraints like the number of weekly harvesting days and purchase location capacities preferred by farmers.
- The study contributes to the literature on harvest optimization as it provides an innovative and sustainable approach by looking at the tea harvesting process in terms of both a farmer and the factory.
- The problem has been tested by a case analysis using real-life data.

4. Application

Real case study and the method used are mentioned in this section.

4.1. Goal programming

Goal Programming (GP) emerged in 1955 with a study by Charnes et al. (Charnes et al., 1955) GP is one of the techniques used in the field of multi-objective decision making and scheduling (Dağdeviren and Eren, 2001). The GP helps to turn all the objectives of the problem into a constraint and to transfer them to the mathematical model. Linear programming helps to decide to optimize only one objective. GP minimizes deviations from multiple goals and helps users to manage contradictory objectives more accurately (Leung et al., 2003). Also, GP models are used for harvest optimization (Rollan et al., 2018). The basic representation of the GP method is as follows:

$$Min\ Z = \sum_{i=1}^{M} (d_i^+ + d_i^-) \tag{1}$$

$$\sum_{j=1}^{n} a_{ij}x_{ij} - d_i^+ + d_i^- = b_i \forall i \tag{2}$$

$$d_i^+ * d_i^- = 0 \forall i \tag{3}$$

$$x_j, d_i^+, d_i^- \geq 0 \forall i \tag{4}$$

Eq. (1) refers to the minimization of deviation variables, which is the objective of the GP method. The constraint that constitutes the deviation variables is shown in Eq. (2). Deviation variables in the GP method are variables that express deviations from specific targets(s). The aim is to minimize these variables in the subject function. This is the most significant difference from GP's linear programming. With deviation variables, a GP model has a feasible solution. For example, a deviation

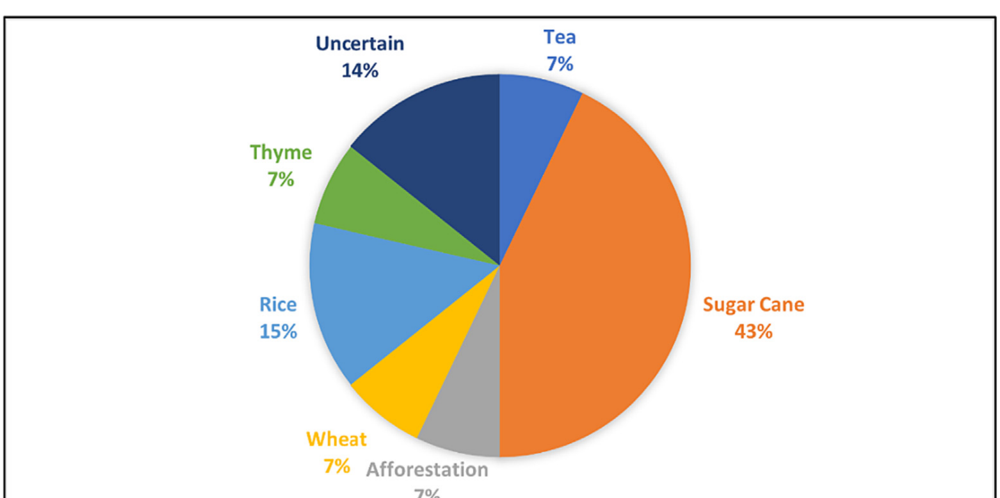


Fig. 2. Distribution of the studies examined by plant species.

variable may mean that a personnel is not appointed to the day he wants. With a GP model, personnel preferences can be followed as much as possible. Eq. (3) refers to the constraint that makes the deviation variables only in one direction. Eq. (4) is a constant of the negative of decision variables and deviation variables. This basic GP model minimizes positive and negative deviations from a goal. With the GP method, only negative or only positive deviations can be minimized, as well as deviations from multiple goals can be minimized. The importance of deviations with the coefficients to be given to the deviation variables can be indicated. Thus, the priority GP model can be installed.

4.2. Tea harvest scheduling

In the study, a harvest optimization was performed on tea harvest scheduling. The flow chart of the application is shown in Fig. 3.

4.3. Problem description

Efficient use of resources is one of the most critical elements affecting the earnings of the factories. The minimum number of truck expeditions required (MNOTER) for each day according to the amount of tea to be harvested by farmers varies. Considering the truck capacities during harvest scheduling, it is essential to reduce the number of expeditions and use the factories' resources efficiently. For this reason, a tea harvest scheduling was made in our study and aimed to minimize the total weekly MNOTER of the factory.

Tea harvest is performed on average three times a year. Procedures to be carried out except harvest: Fertilization, pruning, and cleaning of herbs. The tea does not need irrigation because it grows in wetlands. Therefore, the tea does not require constant attention and follow-up. Because of they plan their daily lives accordingly, it is important to prefer harvest days for the farmers. Farmers who can harvest on the day they prefer will be enthusiastic about tea harvest. This will allow the use of land that is not planted and harvested for tea harvesting. For these reasons, a schedule created by considering the farmer's preferences will directly contribute to sustainability in agriculture. For this reason, a tea harvesting scheduling that considered the farmers' preferences was performed.

Each farmer belongs to a purchase location according to where he resides. Exposure of teas to sunlight burns teas, and some or all of them lead to the rejection of the factory. Because tea became useless for factories. The rejection of these teas, which are fertilized, cleaned from wild herbs, harvested when the time comes, and transported to the purchase locations causes wastage. For this reason, in this study, the capacity of purchase location is considered in the tea harvest scheduling.

4.4. Problem data

The case study was implemented in a region with 988 farmers and 3392 decares of tea fields in Rize. There are 12 purchase locations in this region, and all purchase locations are linked to the same factory. The data were taken from this factory. Each farmer harvests the same amount of tea on their harvest days. The capacity of the factory for the area discussed is 288.000 kg per day. The capacity of the vehicles between the purchase location and the factory is 20.000 kg. The capacity of the purchase location is the same every day and is as given in Table 2.

Decare information on the lands of farmers was obtained. Although the quota varies from period to period, the weekly quota was determined by the expert opinion that it was 500 kg per decare. The weekly quota is essential in terms of fair sales of farmers. Tea can be sold six days a week. In the case study, the number of harvesting days of farmers was taken into consideration. However, these values were not taken from farmers and were determined according to expert opinion and farmer quotas. During the creation of preferences, a variable called normalized value was calculated first. This normalized value consists of the division of the weekly quota of each farmer into the maximum quota. According to this normalized value, the intervals to be used to determine the number of harvesting days was created with the support of expert opinion. Table 3 shows these intervals.

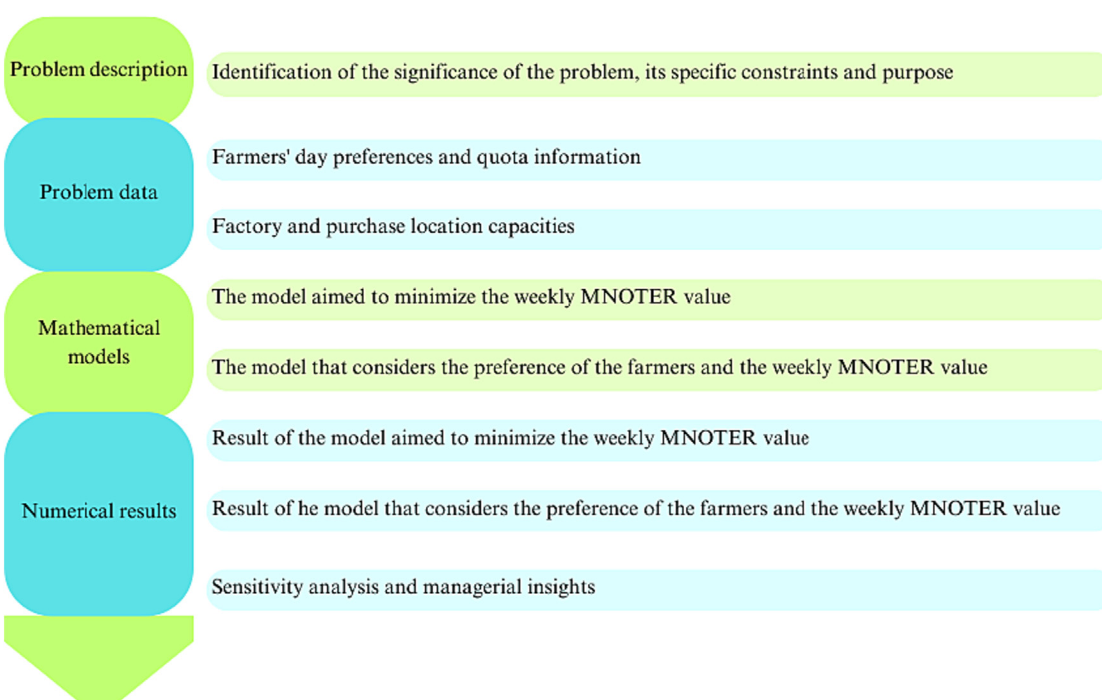


Fig. 3. Flow chart of the application.

Table 2
The capacity of purchase locations per day.

Purchase location	Capacity (kg)
1	32,827
2	33,452
3	25,021
4	12,278
5	16,679
6	11,719
7	14,612
8	37,289
9	41,125
10	31,542
11	17,984
12	20,207

The distribution of farmers according to the number of harvesting days is as in Table 4.

Day preferences of farmers were randomly made according to the number of weekly harvest days. In order to measure the determination of the model, many preference matrices were created in Section 4.6.3 and the effectivity of the model was tested.

4.5. Mathematical models

Two different mathematical models have been developed to produce solutions for farmers and factories for the tea harvest scheduling problem. The features of the models are shown in Table 5. The notations used in mathematical models are given in Table 6.

4.5.1. The model aimed to minimize the weekly MNOTER

This model minimizes the MNOTER complying with farmers' total number of harvesting days, purchasing place, and factory capacity constraints. Minimizing the number of expeditions is essential in terms of the efficient use of factory vehicles. In this model the day preferences of farmers are not taken into consideration.

$$Min\ Z = \sum_{g=1}^{G} n_g \tag{5}$$

Subject to

$$\sum_{g=1}^{G} x_{cg} = \sum_{g=1}^{G} p_{cg} \forall c \tag{6}$$

$$\sum_{c=1}^{C} \left(I_{ca}\, x_{cg} (m_c/g_c) \right) \le k_{ag} \forall a, g \tag{7}$$

$$\sum_{c=1}^{C} \left(x_{cg}\ (m_c/g_c) \right) \le f_g \forall g \tag{8}$$

$$\sum_{c=1}^{C} \left(x_{cg} (\ m_c/g_c\ ) \right) \le \beta\ n_g \forall g \tag{9}$$

$$x_{cg}\ 0\ veya\ 1 \forall c, g \tag{10}$$

Table 3
Normalized value ranges used to determine the number of farmers' weekly harvest days.

Range of normalized value	The number of harvesting days
[0−0,1)	1
[0,1 - 0,15)	2
[0,15 - 0,2)	3
[0,2−0,3)	4
[0,3 - 0,4)	5
[0,4–1]	6

Table 4
Distribution of farmers by weekly harvest days.

The number of harvesting days	Number of farmer
1	363
2	267
3	155
4	144
5	38
6	21

Eq. (5) is the objective function that minimizes the total number of expeditions weekly. Eq. (6) ensures that farmers are assigned as much as they should be assigned according to the number of days they want to harvest. For example, for a farmer who wants to harvest 3 days a week, the $\sum_{g=1}^{G} p_{cg}$ value is 3. Eq. (6) is complied with the number of weekly harvesting days of the farmer by making the $\sum_{g=1}^{G} x_{cg}$ value 3 for this farmer. Eq. (7) refers to the constraints of purchase location capacities. Eq. (8) is the capacity constraint of the factory. It contains the capacity of the factory for the region discussed daily. Eq. (9) refers to the constraint of the minimum number of daily expeditions to be done depending on vehicle capacities (β). Eq. (10) refers to the domains of decision variables.

4.5.2. The model that considers the preference of the farmers and the weekly MNOTER

This model is a multi-objective optimization model. The number of weekly expeditions is minimized, and it is aimed to comply with the farmers' preferences as much as possible. The subject function of the first model was brought to Eq. (11) instead of 5. Eq. (12) and Eq. (13) were included in the model. In this way, the multi-objective optimization model has been created.

$$Min\ Z = k_1 \sum_{c=1}^{C} \sum_{g=1}^{G} d_{cg} + k_2 \sum_{g=1}^{G} n_g \tag{11}$$

Subject to
Eqs. (6)–(10)

$$x_{cg} - p_{cg} + d_{cg} \ge 0 \forall c, g \tag{12}$$

$$d_{cg}\ 0\ veya\ 1 \forall c, g \tag{13}$$

According to the expert opinions received, k_1 is determined as 2 and k_2 as 5. So, the minimization of the number of expeditions is 2.5 times more important than the deviation minimization of farmers' preferences. In other words, increasing the total number of weekly expeditions by two is equivalent to the farmers deviating from the preference of 5 days.

When determining these values by the experts, the extent to which both parameters benefit the tea harvest scheduling problem has been taken into account. Eq. (11) is the objective function, which minimizes the number of weekly expeditions and the deviation of farmers from their preferences. Eq. (12) constitutes the deviation variable from farmers' day preferences. If the farmer prefers for a day but is not assigned, the d_{cg} variable takes on a value of 1 and worsens the object function. Eq. (13) refers to the domains of decision variables.

4.6. Numerical results

In the solution of the mathematical models, a computer with Intel(R) Core(TM) i7-7700HQ CPU @ 2.80GHz 2.81 GHz, 8 GB RAM was used. Solutions were implemented in IBM ILOG CPLEX Optimization

Table 5
Features of developed harvest scheduling mathematical models.

Model	Parameters		Goal	
	Number of days	Which days	Compliance with preferences	Minimizing MNOTER
Model aiming to minimize the weekly MNOTER	Farmer determines	Factory determines		✓
The model that considers the preference of the farmers and the weekly MNOTER	Farmer determines	Farmer prefers	✓	✓

Studio 12.8.0 (COS) and Python 3.7.7 using COS's application programming interface (API).

4.6.1. The solution of the model aimed to minimize the weekly MNOTER

The solution with COS took 1.88 s. It was seen that the object function value of the model was 87, which is the total number of expeditions weekly. According to the result, Monday, Tuesday, and Wednesday, 15 vehicles; other days 14 vehicles were needed. Although this model did not aim to adapt to the farmers' harvest day preference, when the solution result was examined, it was observed that the farmers' preference matrix was complied with by 52.13%. The assignment of 116 farmers to the day preferences of the first purchase location is shown in Table 7. The green cells in the table mean that the farmer preferred that day and was assigned. Red cells mean that the farmer was not assigned even if he preferred. Empty cells mean that the farmer does not prefer that day.

There 267 preferences of the farmers who will sell at the first purchase location. The created schedule complies with the 129-day preference. According to this result, the rate of compliance to the day preferences of the farmers is 48.31%. The rate of compliance of all purchase locations to day preferences is shown in Table 8.

When Table 8 is examined, it is seen that the purchase location with the lowest compliance rate is the 11th purchase location with 41.73%, and the purchase location with the highest compliance rate is the sixth purchase location with 84.06%. Another value that needs to be analyzed is the capacity utilization ratio (CUR) of the purchase location. The daily capacity of the first reception site is 32,827 kg. Table 9 shows the quantities of tea sold at the first purchase location and the CUR values.

When Table 9 is examined, it is seen that the daily purchase location capacity is complied with every day at the first purchase location. Analysis of the CUR values of all purchase locations are shown in Table 10.

Table 10 shows that capacity constraints were observed at all purchase locations on harvest days. This means that the harvested teas will not be exposed to the risk of being left outside and burned.

Table 6
Notations used in mathematical models.

Indexes and parameters	Meaning
c	Index of farmer (1,2, …C)
a	Index of purchase location (1,2, …A)
g	Index of day (1,2, …G)
C	Number of farmers (988)
A	Number of purchase locations (12)
G	Nuber of days (6)
k_{ag}	Capacity of purchase location a, day g (kg)
f_g	Capacity of factory in day g (kg)
β	Capacity of vehicle (kg)
m_c	Weekly quota of farmer c (kg)
I_{ca}	Farmer c sells at purchase location a (1: yes, 0:no)
g_c	How many days a week the farmer c wants to harvest
p_{cg}	Whether farmer c wants to sell on day g, to align with the binary domain.
k_1, k_2	k_1: Weight of compliance with preferences k_2: Weight of MNOTER minimization
Decision variables	**Meaning**
X_{cg}	The assignment of farmer c on day g (1: assigned, 0: not assigned)
n_g	The minimum number of expedition to be done on day g
d_{cg}	Deviation on day g, from farmer c's prefer (1: There is a deviation, 0: not)

4.6.2. The solution of the model that considers the preference of the farmers and the weekly MNOTER

This model is a multi-objective optimization model. It is aimed to minimize deviations from farmers' harvest day preferences and the number of weekly expeditions. The solution with COS took 7.91 s. The object function value of the model was found to be 541. According to the schedule, the total weekly MNOTER value is 87. It was seen that 53 of the farmers' preferences is not assigned. The value of 541 is formed by multiplying 87 by a coefficient of 5, 53 by a coefficient of 2, and then summing up. According to the result, Tuesday, Wednesday, and Saturday, 15 vehicles, other days 14 vehicles were needed. Different results can be obtained by changing the coefficients in the mathematical model. According to the schedule, 2201 out of 2254 days preference were complied with. Accordingly, the adaptation rate to farmers' preferences was calculated as 97.65%. The assignment of 116 farmers to the day preferences of the first purchase location for examination is shown in Table 11. The green cells in the table mean that the farmer preferred that day and was assigned. Red cells mean that the farmer prefers but is not assigned. Empty cells mean that the farmer does not prefer that day.

There are 267 preferences of the farmers who will sell at the first purchase location. The created schedule complies with the 263 days preference. According to this result, the rate of compliance to the day preferences of the farmers is 98,5%. The rate of compliance of all purchase locations to day preferences is shown in Table 12.

When Table 12 is examined, it is seen that the purchase location with the lowest compliance rate is the 12th purchase location with 95.3%, and the purchase location with the highest compliance rate is the sixth purchase location with 100%. Another value that needs to be analyzed is CUR. The daily capacity of the first reception site is 32,827 kg. Table 13 shows the quantities of tea to be sold at the first purchase location and the CUR values.

When Table 13 is examined, it is seen that the daily purchase location capacity is complied with every day at the first purchase location. Analysis of the CUR values of all purchase locations are shown in Table 14.

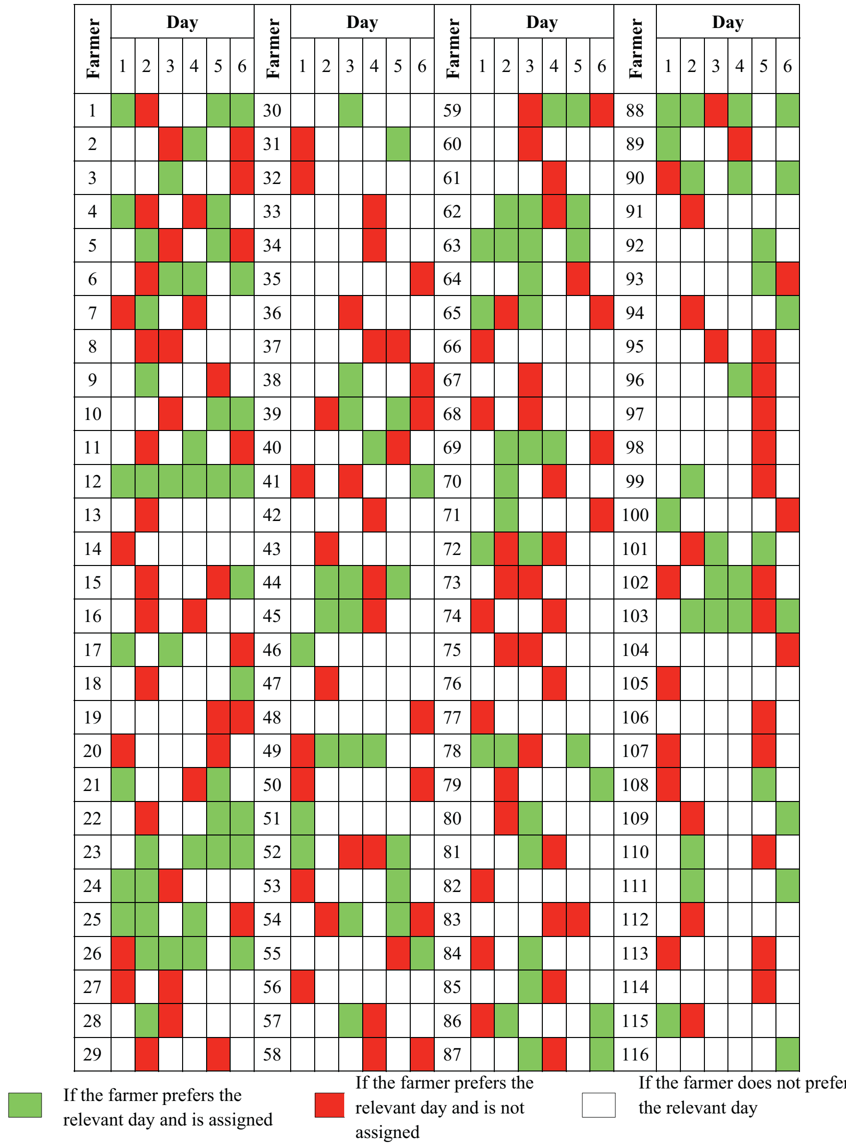
Table 14 shows that capacity constraints were observed at all purchase locations on harvest days. This means that the harvested teas will not be exposed to the risk of being left outside and burned.

4.6.3. Sensitivity analysis and managerial insights

In this section, sensitivity analysis was performed to measure the effectiveness of the developed mathematical models in different preference matrices. In the model aiming to minimize the MNOTER, the effect of the number of weekly harvest days of farmers on the model's success was examined. In the model, which takes into account the preferred days of the farmers and the weekly MNOTER, the effect of the farmers' day preferences on the model's success was examined while the weekly harvest day numbers were fixed.

In the model aimed at minimizing the weekly MNOTER, some of the harvest day numbers of farmers were modified to examine the effect of

Table 7
According to the results of the model that aimed minimization of the weekly MNOTER, compliance to the day preferences of farmers at the first purchase location.



the number of weekly harvest days on the model's success. The farmers to be modified were randomly selected. The weekly harvest day numbers of the selected farmers were again randomly changed by one day in the upward or downward direction. There has been no change in the upward direction for those whose number of harvest days is six and downward for those who have one. The reason for changing only one day is to maintain the reasonableness of the number of harvest days established by considering the farmer's weekly quota. For example, it would not be reasonable for a farmer who harvests a large amount of tea six days a week to change the number of harvest days per week to one. In this way, 100 preference matrices were produced with Python. Solutions have been implemented through Python and COS. When the results were examined, it was seen that the weekly MNOTER was 87 in all of the solutions, and changing the number of harvest days did

Table 8
According to the results of the model that aimed minimization of the weekly MNOTER, compliance to the day preferences of farmers in all purchase location.

Purchase location	Number of farmers	Number of prefers	Number of complience	Rate of complience
1	116	267	129	48.31%
2	114	255	126	49.41%
3	101	199	90	45.23%
4	45	86	38	44.19%
5	54	124	59	47.58%
6	15	69	58	84.06%
7	42	115	68	59.13%
8	148	282	126	44.68%
9	128	319	198	62.07%
10	101	250	129	51.60%
11	71	139	58	41.73%
12	53	149	96	64.43%

Table 9
According to the results of the model that aimed minimization of the weekly MNOTER, quantities of tea to be sold at the first purchase location and CUR values.

Day	Quantity of harvest (kg)	CUR
1	32,034.13	97.58%
2	32,747.33	99.76%
3	32,480.42	98.94%
4	29,791.88	90.75%
5	31,253.17	95.21%
6	32,653.58	99.47%

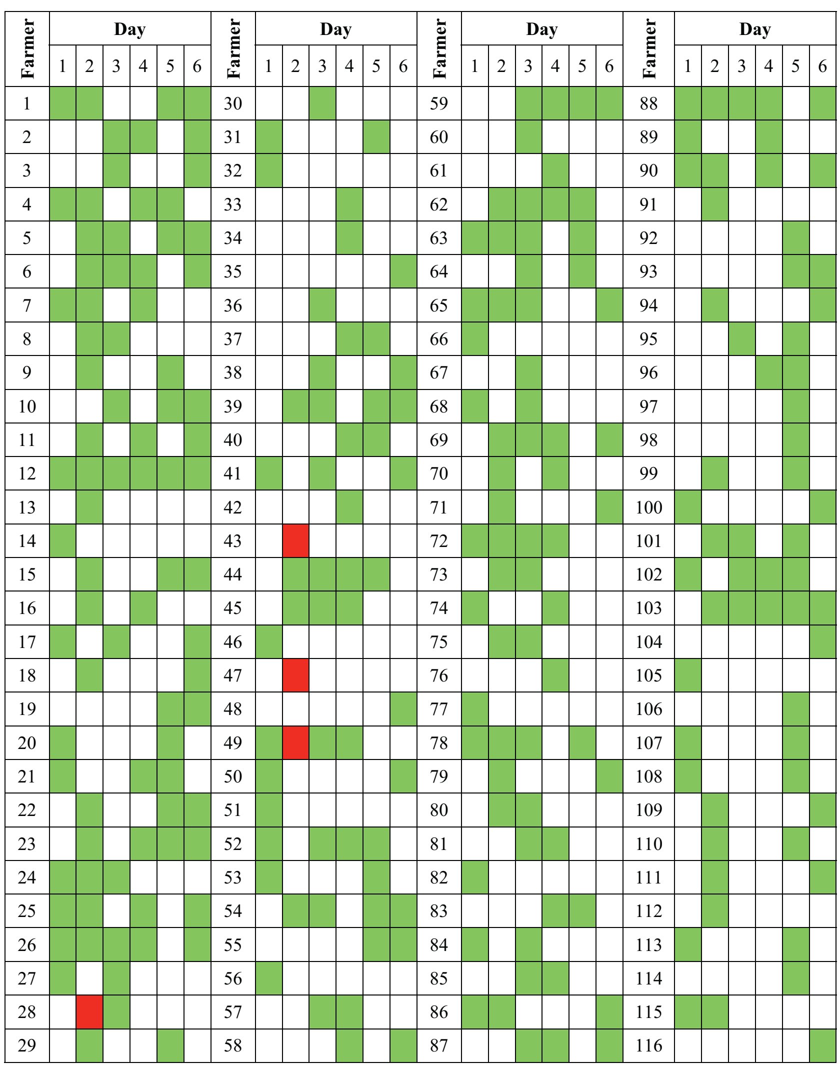
Table 10
According to the results of the model that aimed minimization of the weekly MNOTER, CUR values of all purchase locations.

Purchase location	Capacity (Kg)	CUR values for days						Minimum CUR	Max CUR	Average CUR
		1	2	3	4	5	6			
1	32,827	97.6%	99.8%	98.9%	90.8%	95.2%	99.5%	90.8%	99.8%	97%
2	33,452	96.3%	97%	94.1%	96.5%	99.3%	98.9%	94.1%	99.3%	97%
3	25,021	99.2%	98.5%	99.6%	99.6%	87.1%	92%	87.1%	99.6%	96%
4	12,278	91.2%	97.5%	96.3%	80.7%	86.3%	99.2%	80.7%	99.2%	91.9%
5	16,679	98.6%	95.9%	94.7%	92.8%	97.2%	84.8%	84.8%	98.6%	94%
6	11,719	95.3%	94.4%	93.2%	95.3%	87.7%	82.8%	82.8%	95.3%	91.5%
7	14,612	98.2%	96.5%	87%	91.8%	99.4%	85.9%	85.9%	99.4%	93.2%
8	37,289	99.5%	97.4%	99.1%	99.1%	94.7%	94.1%	94.1%	99.5%	97.3%
9	41,125	92.8%	99.8%	99.8%	96.1%	97.3%	99.7%	92.8%	99.8%	97.6%
10	31,542	98.3%	99.4%	98.8%	90.6%	99.9%	94.1%	90.6%	99.9%	96.8%
11	17,984	97.9%	85.3%	96.5%	98.3%	90.6%	98%	85.3%	98.3%	94.4%
12	20,207	99.7%	95.3%	99.1%	99.4%	92.9%	83.9%	83.9%	99.7%	95%

not change this value. This result proves that the model maintains its effectiveness in different matrices.

In the model, which considers the preferred days of farmers and the weekly MNOTER, the farmers' harvest day preferences were randomly changed without changing the number of harvest days. In this way, 100 preference matrices are produced with Python. Solutions have been implemented through Python and COS. When the results were examined, it was seen that the weekly MNOTER was 87 in all solutions.

Table 11
According to the results of the model that considers the preference of the farmers and the weekly MNOTER, compliance to the day preferences of farmers at the first purchase location.



If the farmer prefers the relevant day and is assigned

If the farmer prefers the relevant day and is not assigned

If the farmer does not prefer the relevant day

Table 12
According to the results of the model that considers the preference of the farmers and the weekly MNOTER, compliance to the day preferences of farmers in all purchase location.

Purchase location	Number of farmers	Number of prefers	Number of complience	Rate of complience
1	116	267	263	98.50%
2	114	255	250	98.04%
3	101	199	193	96.98%
4	45	86	83	96.51%
5	54	124	120	96.77%
6	15	69	69	100%
7	42	115	112	97.39%
8	148	282	277	98.23%
9	128	319	316	99.06%
10	101	250	243	97.20%
11	71	139	133	95.68%
12	53	149	142	95.30%

Table 13
According to the results of the model that considers the preference of the farmers and the weekly MNOTER, quantities of tea to be sold at the first purchase location and CUR values.

Day	Quantity of harvest (kg)	CUR
1	32,156.96	97.96%
2	32,773.08	99.84%
3	32,544.04	99.14%
4	29,174.88	88.87%
5	32,022.25	97.55%
6	32,289.29	98.36%

The fact that the value is 87 again shows that the change in farmers' harvest day preferences does not affect the weekly MNOTER. The average rate of adaptation to farmers' preferences was calculated as 97.12%. Fig. 4 shows the compliance rate of 100 solutions to farmer preferences.

When Fig. 4 is examined, it is seen that the preference compliance rate is the worst 95.96% and the best 98.05%. Therefore, it was concluded that farmer preferences could not be fully complied with, and in the worst case, farmer preferences could be complied with 95% of the time. Therefore, the absence of a value lower than 95% in the sensitivity analysis proves the model's effectiveness.

The two mathematical models developed were examined according to the parameters of adaptation to the farmers' day preferences and the weekly MNOTER of the factory. This review is shown in Table 15. The * symbols in the table indicate that the model is intended to optimize the value in question.

When the models are examined in terms of adaptation to farmer preferences, it is seen that the model aiming at minimization of the weekly MNOTER has lower success. This is because the model does not consider farmer preferences. When the MNOTER is examined, it is seen that the consideration of farmer preferences does not affect this value. Although the weekly MNOTER is the same, the second model offers a dominant solution compared to the first model because the second model is better at adapting to preferences. This proves that while considering farmers' day preferences, the weekly MNOTER of the factories can also be minimized. Subjecting the models to sensitivity analysis and deciding their consistency shows they will succeed in different preference matrices.

According to the results obtained, the following predictions are made to the managers:

- By considering the weekly MNOTER during tea harvest scheduling, the competitiveness of tea producers in sales prices will increase as factory resources will be used more efficiently.
- Considering the capacities of the purchase location is important for the sake of not losing the harvest, efficient use of the receiving places, and the sustainability of the farmer-factory relationship. In addition, as a result of analysing the occupancy rates of the reception place, it may be considered to make the purchase locations with low CUR value inactive on certain days. In this way, the shipping program can become more efficient.
- The case study proven that considering the farmers' harvest day preferences during harvest scheduling will not create any cost to the factory. On the contrary, considering farmers' preferences is important to increase sustainability in agriculture.
- Compliance with farmers' harvest day preferences and accordingly purchasing the farmers' harvest from the purchase locations will increase the preferability of tea-producing companies. As a result, companies will increase their competitiveness and get one step ahead in the market.

5. Conclusion

In the study, a harvest optimization for sustainable agriculture was carried out. Two mathematical models have been developed for tea harvest scheduling. One of these models only optimizes factory resources, while another aims to comply with factory resources and farmer preferences as much as possible. A case study was conducted in a region with 3392 decares tea fields, 12 tea receiving places and a factory. The schedule created with the models is compared in terms of the number of expeditions made by the factory vehicles and the adaptation to the day preferences of the farmers. According to the mathematical model, which only considers the number of expeditions of factory vehicles, it

Table 14
According to the results of the model that considers the preference of the farmers and the weekly MNOTER, CUR values of all purchase locations.

Purchase location	Capacity (Kg)	CUR values for days						Minimum CUR	Max CUR	Average CUR
		1	2	3	4	5	6			
1	32,827	98%	99.8%	99.1%	88.9%	97.5%	98.4%	88.9%	99.8%	97%
2	33,452	98.8%	99.2%	100%	97.8%	87.1%	99.1%	87.1%	100%	97%
3	25,021	98.5%	90.3%	98.7%	98.5%	90.3%	99.7%	90.3%	99.7%	96%
4	12,278	79.6%	98.9%	80.9%	97.6%	96.7%	97.3%	79.6%	98.9%	91.9%
5	16,679	79.7%	95.9%	95.6%	99.7%	98.1%	95%	79.7%	99.7%	94%
6	11,719	95.2%	99.8%	84.6%	86.2%	89.3%	93.8%	84.6%	99.8%	91.5%
Purchase location	Capacity (Kg)	CUR values for days						Minimum CUR	Max CUR	Average CUR
		1	2	3	4	5	6			
7	14,612	93.1%	82.7%	99.3%	96.4%	93.2%	94.1%	82.7%	99.3%	93.2%
8	37,289	98.2%	99.7%	98.3%	98.7%	97.3%	91.6%	91.6%	99.7%	97.3%
9	41,125	91.3%	99.1%	98.3%	98%	99.5%	99.1%	91.3%	99.5%	97.6%
10	31,542	99.2%	98.8%	95.4%	89.2%	99.6%	98.7%	89.2%	99.6%	96.8%
11	17,984	95.7%	99.8%	91.4%	85.3%	97.2%	97.2%	85.3%	99.8%	94.4%
12	20,207	95.1%	98.7%	93.3%	98.2%	85.1%	100%	85.1%	100%	95%

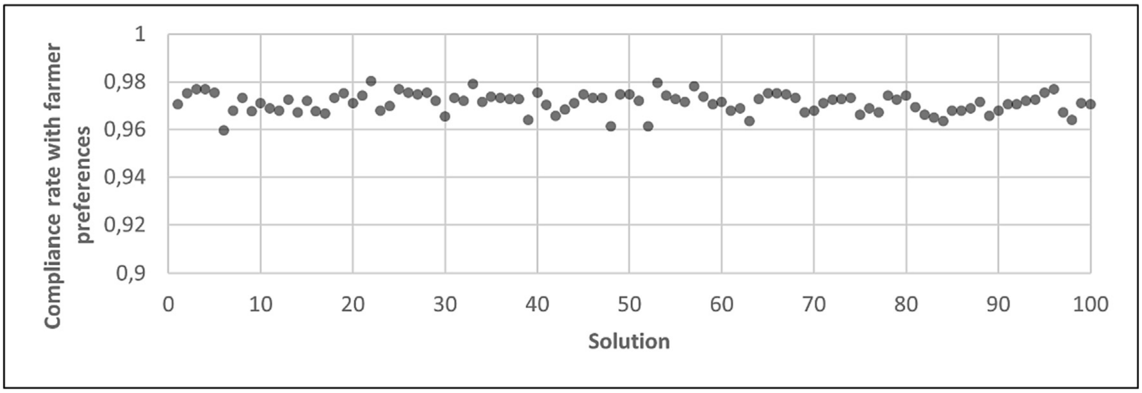


Fig. 4. The rate of adaptation to farmer preferences of solutions.

Table 15
Comparison of the achievements of mathematical models.

Model	Adaptation to farmers' preferences	Weekly MNOTER
The model that aimed minimization of the weekly MNOTER	52.13%	87*
The model that considers the preference of the farmers and the weekly MNOTER	97.65%*	87*

is seen that 87 expeditions per week are required and the rate of adaptation to farmer preferences is 52.13%. In the model, which considers the day preferences of farmers and factory vehicles, it was seen that while the number of expeditions remained the same, the rate of adaptation to farmers' day preferences increased from 52.13% to 97.65%. This result shows that considering the farmers' day preferences does not negatively impact the factory and can increase sustainability and incentives in agriculture. Companies can increase their preference by considering the farmers' harvest day preferences and get one step ahead in the market.

In future studies, vehicle routing and personnel scheduling problems may also be included in the tea harvest scheduling problem. It can be decided which days the farmers will harvest, which route the factory's vehicles will follow, and which purchase locations will stop. Staff scheduling studies can be carried out for drivers and purchase location officers. The effect of making farmers' buying places flexible on the rate of adaptation to their day preferences can be examined. Larger problems can be addressed, and scheduling can be carried out for all reception locations connected to the factory. As the complexity of models increases, solutions can be realized with heuristic methods.

CRediT authorship contribution statement

Bedirhan Sarımehmet: Data Curation, Methodology, Resources, Software, Writing - original draft. **Hacı Mehmet Alakaş:** Conceptualization, Supervision, Writing - review & editing. **Mehmet Pınarbaşı:** Conceptualization, Formal analysis, Supervision, Writing - original draft, Writing - review & editing. **Tamer Eren:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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