Collaborative Optimization Tool for Sustainable Planning of an Agricultural Supply Chain Preserving Farmers' Independence

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Abstract. Farmers often decide independently when and how much area to plant each crop. As farmers unknow the demand for crops, they tend to plant the most profitable crops from the previous year. If all farmers reproduced this behavior, they would overproduce the most profitable crops and underproduce the least profitable ones, leading to a supply-demand imbalance and price fluctuations. To solve this problem while maintaining farmers independence, a collaborative optimization-based tool is proposed that allows to centrally define the minimum and maximum proportion of area to be planted with each crop and in each period to be sustainable in terms of profits, waste, and unmet demand, and to use this proportions to independently define the planning of planting, harvesting and crop distribution for each farmer. The proposed tool is assessed by determining and comparing what the supply chain outcomes would be if farmers used the collaborative tool or not.

Keywords: Collaborative, Crop planning, Agri-food, Perishable, Optimization.

1 Introduction

In the agri-food sector, farmers usually make decisions about how much area to plant each vegetable and/or fruit and when to plant them independently and without considering the decisions made by other farmers [1]. As farmers have no information about the demand and supply for the crops when making such decisions, they tend to plant those crops that had a higher economic margin in the previous year [2].

If all farmers act in this way, there will be an oversupply of those crops that were most profitable in the previous year and a shortage of those that were not so profitable [3]. This imbalance of supply and demand results in the wastage of some crops and the impossibility of meeting the full demand for others, which negatively affects the environmental and social sustainability of the supply chains (SCs). In addition, crop prices fluctuate according to the balance between demand and supply, rising when supply is lower than demand and falling when there is an excess of crop over demand [4], which also impacts on the economic sustainability of the SC.

There are multiple mathematical programming models that support the crop planting planning process that aim to balance supply and demand. However, most proposals rely on centralized decision-making in which farmers lose independence in crop planting [5–7]. Up to our knowledge, only [1] propose distributed models for crop planting planning. concluding that their results are not sustainable for the SC.

In this context, it is intended to answer the following research question: Is it possible to establish a collaborative tool to balance crop supply and demand and increase the SC sustainability while maintaining farmers' independence?

To solve this question, a collaborative tool based on multi-objective mixed integer linear programming models is proposed. This tool establishes in a first step the minimum and maximum proportion of area to be planted with each crop and in each planting period to balance crop supply and demand and to achieve economic, environmental, and social sustainability. In a second step farmers independently choose the area to be planted with each crop, respecting the proportions set in the first step.

This approach is common in some countries, where government agencies advise farmers on the areas to be planted with each crop and in each planting period to have a greater control over markets and prices.

In addition, this paper assesses the results obtained with the collaborative tool and compares them to those that would be obtained if farmers acted completely independently, thus validating the proposed tool and showing its main advantages.

The rest of the article is structured as follows. Section 2 describes the problem under study. Section 3 proposes the collaborative tool and the resolution methodology. Section 4 validates the collaborative tool through its application to a case study and tests the advantages of implementing the proposed tool. Finally, section 5 outlines the main conclusions and future lines of research.

2 Problem Description

The problem addressed in this paper is the collaborative planning of planting, harvesting, distribution and sale of crops in a SC composed of multiple farms and markets. The SC commercialises multiple crops that have a limited shelf life.

Markets require crops to have a minimum shelf-life at the time of sale to be accepted.

Fig. 1 shows the composition of the SC as well as the main decisions or activities, carried out by each of its actors, that are considered in this paper. Thus, farmers are responsible for planting, cultivating, harvesting the area defined for each crop, storing, and packing the harvested crops, and transporting them to markets. Once they reach the markets, the crops are sold to the final consumers.

In addition, if the shelf-life of the product is shorter than required by the market during storage or while they are on the market, they are wasted. On the other hand, if the supply of the product is less than the demand, unsatisfied demand is generated.

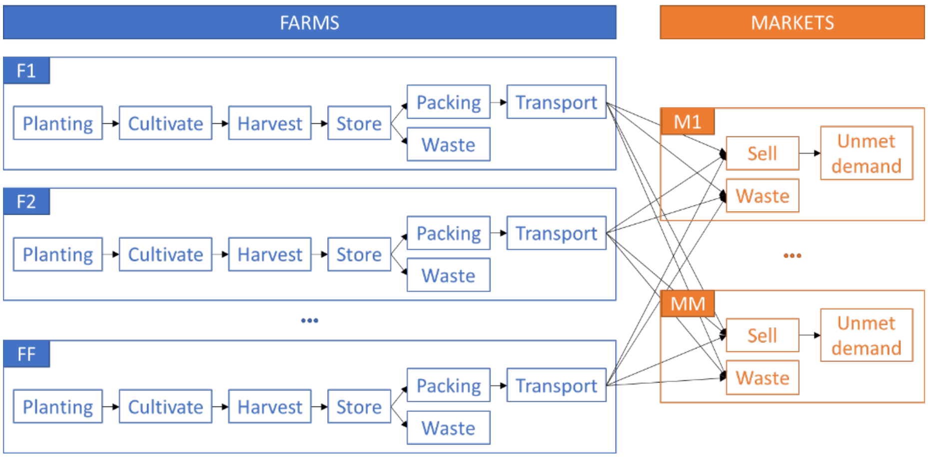

Fig. 1. SC configuration and activities.

Moreover, the following assumptions are considered:

- The area available on the farms can be planted in different weeks in the same year but can only be planted once.
- The planting, cultivation and harvesting calendar is known for each type of crop. The cultivation and harvesting periods are dependent on the planting period.
- The yield of the plants is known and depends on the planting and harvesting period of the plants.
- Once harvested, crops have a limited shelf-life.
- Harvested crops can be stored on farm until their shelf-life is lower than the required by the markets.
- The crops are packed on the farms and transported to the markets in the same period of their packing.

- All crops that reach the market are sold if supply is less than or equal to demand. In this case, unsatisfied demand could be generated.
- If the supply of crops in the markets is higher than the demand, wastage is generated in the markets.
- The aim is to achieve planning sustainability by maximizing profits, minimizing wastage, and minimizing unsatisfied demand.

3 Collaborative Tool

This section proposes a collaborative tool to plan the planting, harvesting, distribution and sale of multiple crops that allows balancing supply and demand of multiple crops in a sustainable way while preserving farmers' individually.

The tool is composed of three stages (Fig. 2). For the first stage, a centralized mixed integer linear programming model is formulated to plan the planting, harvesting, distribution, and sale of the crops and to establish the minimum and maximum proportion of area to be planted with each crop and in each planting period in order to balance supply and demand. This model aims for sustainability of the SC by maximizing profit (economic), minimizing waste (environmental), and minimizing unsatisfied demand (social).

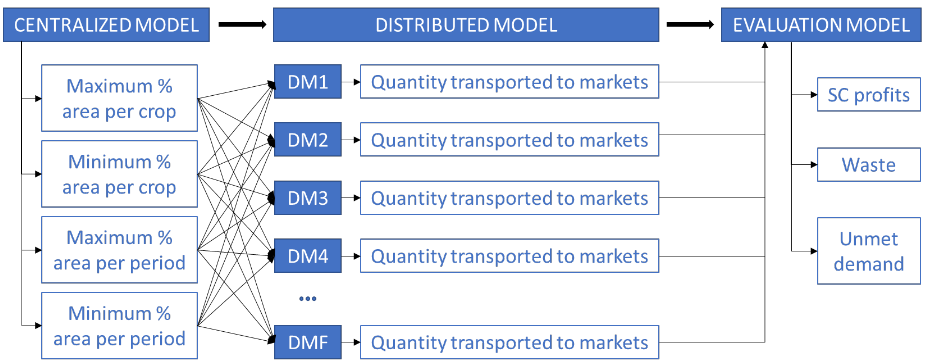

Fig. 2. Collaborative tool.

For the second stage, a distributed mixed integer linear programming model is formulated that allows farmers to plan the planting, harvesting, distribution and sale of crops separately and independently. This model considers the minimum and maximum proportion of area to be planted with each crop obtained in the first stage as an input. Therefore, farmers' independence is not unrestricted but controlled. Since at this level farmers have no information on market demand and supply from other farmers, it is assumed that all crops transported from farms to markets are sold.

Given that the entire quantity transported may not be finally sold to the markets due to existing demand, and to test the validity and advantages of the proposed collaborative tool, an assessment model is formulated. This model draws on the quantities of crops that farmers have decided to transport to the markets and derives what the actual profits, wastage and unsatisfied demand in the SC will be.

3.1 Centralized Model Formulation

Table 1 shows the notation used to formulate the centralized model to define the minimum and maximum proportion of area to be planted with each crop and in each planting period.

Table 1. Notation for the centralized model.

Indices	
c	Crop ($c = 1, \dots, C$)
p	Planting period ($p = 1, \dots, P$)
h	Harvest period ($h = 1, \dots, H$)
t	Time period ($t = 1, \dots, T$)
f	Farm ($f = 1, \dots, F$)
m	Market ($m = 1, \dots, M$)
x	Freshness of crop ($x = sl_c + h - t$)
Set of indices	
P_c	Set of periods p in which the crop c can be planted
H_c	Set of periods h in which the crop c can be harvested
PC_c^p	Set of periods t in which crop c is to be cultivated (activities related to irrigation, application of phytosanitary products, among others) if it is planted in period p
PH_c^p	Set of periods h in which crop c is to be harvested if it is planted in period p
HP_c^h	Set of periods p in which crop c can be planted to be harvested in period h
Parameters	
a_f	Area available for planting on farm f
am_c	Minimum area to be planted with crop c in case of planting due to technical reasons
ma	Maximum difference between the minimum and maximum planting area ratio
y_c^{ph}	Yield of crop c if planted in period p and harvested in period h
sl_c^h	Shelf-life of crop c if harvested in period h
msl_c	Minimum shelf-life required by the markets for the sale of crop c

d_{cm}^{t}	Demand for crop c in market m and in period t
sp_{cm}^{tx}	Selling price of a kilogram of crop c with freshness x on market m in period t
cpc_c	Cost of planting and cultivating one hectare of crop c
ch_c	Cost of inventorying one kilogram of crop c during a period
ct_{cfm}	Cost of transporting one kilogram of crop c between farm f and market m
Decision variables	
AP_{cf}^{p}	Area planted with crop c on farm f in planting period p
$AMinc_c$	Minimum proportion of the area to be planted with crop c
$AMaxc_c$	Maximum proportion of the area to be planted with crop c
$AMinp_p$	Minimum proportion of the area to be planted in planting period p
$AMaxp_p$	Maximum proportion of the area to be planted in planting period p
YP_{cf}^{p}	Binary variable with value 1 if crop c is planted on farm f in period p, and 0 if not
AC_{cf}^{t}	Area planted with crop c on farm f cultivated in period t
AH_{cf}^{ph}	Area planted with crop c on farm f in period p and harvested in period h
QH_{cf}^{h}	Quantity of crop c harvested on farm f in harvest period h
QP_{cf}^{ht}	Quantity of crop c harvested on farm f in period h and packed in period t
WF_{cf}^{ht}	Quantity of crop c harvested on farm f in period h and wasted in period t
I_{cf}^{ht}	Quantity of crop c harvested on farm f in period h and inventoried in period t
QT_{cfm}^{ht}	Quantity of crop c harvested on farm f in h and transported to market m in period t
WM_{cm}^{ht}	Quantity of crop c harvested on market m in period h and wasted in period t
QS_{cm}^{ht}	Quantity of crop c harvested in period h and sold at market m in period t
U_{cm}^{t}	Quantity of unsatisfied demand for crop c at market m in period t

The model has three objectives aligned with the three pillars of sustainability. The economic objective is to maximize profits from the SC and consists of sales and costs related to planting and cultivation of crops, storage, and transport (1). The environmental objective is the minimization of waste generated and consists of crop waste at farms and at markets (2). The social objective consists of minimizing the unsatisfied demand for crops (3), ensuring the meeting of the human needs, and increasing the consumers' satisfaction.

$$Max\ Z_{EC_C} = \sum_{c}\sum_{m}\sum_{h\in H_c}\sum_{t} sp_{cm}^{tx=sl_c+h-t} \cdot QS_{cm}^{ht} - \sum_{c}\sum_{f}\sum_{p\in P_c} cpc_c \cdot AP_{cf}^{p} - \sum_{c}\sum_{f}\sum_{h\in H_c}\sum_{t} ch_c \cdot I_{cf}^{ht} - \sum_{c}\sum_{f}\sum_{m}\sum_{h\in H_c}\sum_{t} ct_{cfm} \cdot QT_{cfm}^{ht} \tag{1}$$

$$Min\ Z_{ENV_C} = \sum_{c}\sum_{f}\sum_{h\in H_c}\sum_{t} WF_{cf}^{ht} + \sum_{c}\sum_{m}\sum_{h\in H_c}\sum_{t} WM_{cm}^{ht} \tag{2}$$

$$Min\ Z_{SOC_C} = \sum_{c}\sum_{m}\sum_{t} U_{cm}^{t} \tag{3}$$

The centralized model is subject to the following constraints.

The area planted on each farm with all crops in all planting periods cannot exceed the area available on the farm (4).

$$\sum_{c}\sum_{p\in P_c} AP_{cf}^{p} \le a_f \qquad \forall f \tag{4}$$

The total area panted with each crop on each farm must be between the minimum and maximum area ratio defined for each crop (5).

$$a_f \cdot AMinc_c \le \sum_{p\in P_c} AP_{cf}^{p} \le a_f \cdot AMaxc_c \qquad \forall c,f \tag{5}$$

The total area planted in each period on each farm must be between the minimum and maximum area ratio defined for each planting period (6).

$$a_f \cdot AMinp_p \le \sum_{c} AP_{cf}^{p} \le a_f \cdot AMaxp_p \qquad \forall f,p \tag{6}$$

The ratio of minimum area to be planted will all crops (7) and in all planting periods (8) must be less than unity, which is equivalent to the total area to be planted.

$$\sum_{c} AMinc_c \le 1 \tag{7}$$

$$\sum_{p} AMinp_p \le 1 \tag{8}$$

The difference between the maximum and minimum proportion of area to be planted with each crop (9) and in each period (10) may not exceed the fixed limit.

$$AMaxc_c - AMinc_c \le ma \qquad \forall c \tag{9}$$

$$AMaxp_p - AMinp_p \le ma \qquad \forall c \tag{10}$$

In case it is decided to plant a crop in one period, a minimum area must be planted due to technological reasons (11).

$$am_c \cdot YP_{cf}^{p} \le AP_{cf}^{p} \le a_f \cdot YP_{cf}^{p} \qquad \forall c,f,p\in P_c \tag{11}$$

The entire planted area must be cultivated (12) and harvested (13) in the required periods, which depend on the planting period.

$$AC_{cf}^{t} = \sum_{p\in PC_c^t} AP_{cf}^{p} \qquad \forall c,f,t \tag{12}$$

$$AH_{cf}^{ph} = AP_{cf}^{p} \qquad \forall c,f,p\in P_c, h\in PH_c^p \tag{13}$$

The quantity of harvested crops depends on the yield of the plants, which is different depending on the planting and harvesting period and the crop (14).

$$\sum_{p\in HP_c^h} y_c^{ph} \cdot AH_{cf}^{ph} = QH_{cf}^{h} \qquad \forall c,f,h\in H_c \tag{14}$$

The harvested crops can be stored, packed, or wasted (15). These crops can be kept in storage until the shelf-life of the crops is less than that required by the markets (16), at which point they cannot be inventoried (17).

$$I_{cf}^{ht} = QH_{cf}^{h} - QP_{cf}^{ht} - WF_{cf}^{ht} \qquad \forall c,f,h\in H_c, t=h \tag{15}$$

$$I_{cf}^{ht} = I_{cf}^{ht-1} - QP_{cf}^{ht} - WF_{cf}^{ht} \qquad \forall c, f, h \in H_c, h < t \leq h + sl_c^h - msl_c \quad (16)$$

$$I_{cf}^{ht} = 0 \qquad \forall c, f, h \in H_c, t = h + sl_c^h - msl_c \quad (17)$$

The packed crops are transported within the same period of their packing to the markets (18), where they can be sold or wasted (19).

$$QP_{cf}^{ht} = \sum_{m} QT_{cfm}^{ht} \qquad \forall c, f, h \in H_c, h \leq t \leq h + sl_c^h - msl_c \quad (18)$$

$$\sum_{f} QT_{cfm}^{ht} = QS_{cm}^{ht} + WM_{cm}^{ht} \qquad \forall c, m, h \in H_c, h \leq t \leq h + sl_c^h - msl_c \quad (19)$$

In the case of insufficient crop availability to serve the demand, unsatisfied demand is produced (20).

$$\sum_{h \in H_c} QS_{cm}^{ht} + U_{cm}^{t} = d_{cm}^{t} \qquad \forall c, m, t \quad (20)$$

Finally, the nature of the decision variables is defined (20).

$$AP_{cf}^{p}, AC_{cf}^{t}, AH_{cf}^{ph}, QH_{cf}^{h}, I_{cf}^{ht}, QP_{cf}^{ht}, QT_{cfm}^{ht}, QS_{cfm}^{ht}, WF_{cf}^{ht}, WM_{cm}^{ht}, U_{cm}^{t}\ CONTINU \quad (21)$$

$$YP_{cf}^{p} \qquad BINARY$$

3.2 Distributed Model Formulation

Table 2 shows the additional notation used to formulate the distributed model for planning the planting, harvesting, distribution and sale of crops on a farm.

Table 2. Notation added for the distributed model.

Parameters	
a	Area available for planting on farm
ct_{cfm}	Cost of transporting one kilogram of crop c between farm f and market m

Table 3. Notation added for the distributed model (continued)

Decision variables	
AP_c^p	Area planted with crop c in planting period p
YP_c^p	Binary variable with value one if crop c is planted in period p, and zero if not
AC_c^t	Area planted with crop c cultivated in period t
AH_c^{ph}	Area planted with crop c in period p and harvested in period h
QH_c^h	Quantity of crop c harvested in harvest period h
QP_c^{ht}	Quantity of crop c harvested in period h and packed in period t
WF_c^{ht}	Quantity of crop c harvested in period h and wasted in period t
I_c^{ht}	Quantity of crop c harvested in period h and inventoried in period t
QT_{cm}^{ht}	Quantity of crop c harvested in period h and transported to market m in period t

The distributed model considers the economic and environmental objectives analogous to those of the centralized model but focused on a single farm. The economic objective is to maximize the farmer's profit, which is made up of sales and costs related to planting and cultivating crops, storage, and transport (22). The environmental objective is to minimize waste generated on the farm (23). The social objective of minimizing unsatisfied demand is not considered at this stage as farmers do not have information on market demand.

$$Max\ Z_{EC_D} = \sum_{c}\sum_{m}\sum_{h\in H_c}\sum_{t} sp_{cm}^{tx=t-h}\cdot QT_{cm}^{ht} - \sum_{c}\sum_{p\in P_c} cpc_c \cdot AP_c^p - \sum_{c}\sum_{h\in H_c}\sum_{t} ch_c \cdot I_c^{ht} - \sum_{c}\sum_{m}\sum_{h\in H_c}\sum_{t} ct_{cm}\cdot QT_{cm}^{ht} \tag{22}$$

$$Min\ Z_{ENV_D} = \sum_{c}\sum_{h\in H_c}\sum_{t} WF_c^{ht} \tag{23}$$

The model is subjected to the constraints (24)-(35) which are analogous to those in the centralized model (4)-(6), (11)-(19). In these constraints, $AMinc_c$, $AMaxc_c$, $AMinp_p$, and $AMaxp_p$ act as parameters and not as decision variables. The nature of the variables is defined (34).

$$\sum_{c}\sum_{p\in P_c} AP_c^p \le a \tag{24}$$

$$a\cdot AMinc_c \le \sum_{p\in P_c} AP_c^p \le a\cdot AMaxc_c \qquad \forall c \tag{25}$$

$$a_f\cdot AMinp_p \le \sum_{c} AP_c^p \le a_f\cdot AMaxp_p \qquad \forall f,p \tag{26}$$

$$am_c\cdot YP_c^p \le AP_c^p \le a_f\cdot YP_c^p \qquad \forall c,p\in P_c \tag{27}$$

$$AC_c^t = \sum_{p\in PC_c^t} AP_c^p \qquad \forall c,t \tag{28}$$

$$AH_c^{ph} = AP_c^p \qquad \forall c,p\in P_c, h\in PH_c^p \tag{29}$$

$$\sum_{p\in HP_c^h} y_c^{ph}\cdot AH_c^{ph} = QH_c^h \qquad \forall c,h\in H_c \tag{30}$$

$$I_c^{ht} = QH_c^h - QP_c^{ht} - WF_c^{ht} \qquad \forall c,h\in H_c, t=h \tag{31}$$

$$I_c^{ht} = I_c^{ht-1} - QP_c^{ht} - WF_c^{ht} \qquad \forall c,h\in H_c, h<t \le h+sl_c^h - msl_c \tag{32}$$

$$I_c^{ht} = 0 \qquad \forall c,h\in H_c, t=h+sl_c^h - msl_c \tag{33}$$

$$QP_c^{ht} = \sum_{m} QT_{cm}^{ht} \qquad \forall c,h\in H_c, h\le t \le h+sl_c^h - msl_c \tag{34}$$

$$AP_c^p, AC_c^t, AH_c^{ph}, QH_c^h, I_c^{ht}, QP_c^{ht}, QT_{cm}^{ht}, WF_c^{ht} \quad CONTINUOUS \tag{35}$$

$$YP_c^p \quad BINARY$$

3.3 Evaluation Model Formulation

To assess the impact of farmers' independent decisions on SC outcomes, a third evaluation model is defined, that is composed of the objective functions defined in the centralized model (1)-(3) and the constraints (19)-(20) that regulate the sales of the crops that are transported to the markets from farms. Therefore, the model receives as input data the values of AP_{cf}^{p}, QT_{cfm}^{ht}, I_{cf}^{ht} and WF_{c}^{ht} obtained in the distributed models that are needed for the calculation of the real sales and values of the objective functions.

3.4 Resolution Methodology

To solve the multi-objective models, the weighted sum method is used. This consists of assigning weights to the objectives according to their relative importance in order to construct a single objective function. The weights assigned to the objectives must add up to 100%. Thus, w_{EC} is the weight assigned to profit maximization, w_{ENV} is the weight assigned to waste minimization, and w_{SOC} is the weight assigned to minimizing unsatisfied demand. In addition, since each objective has a different order of magnitude, each of its values is divided by the maximum value that it can acquire so that the values obtained are between zero and one.

Thus, the centralized model would be as follows:

$$Max\ Z_C = w_{EC_C} \cdot \frac{Z_{EC_C}}{maxZ_{EC_C}} - w_{ENV_C} \cdot \frac{Z_{ENV_C}}{maxZ_{ENV_C}} - w_{SOC_C} \cdot \frac{Z_{SOC_C}}{maxZ_{SOC_C}} \tag{36}$$

Subject to: (4)-(21)

The formulated of the distributed model would be as follows:

$$Max\ Z_D = w_{EC_D} \cdot \frac{Z_{EC_D}}{maxZ_{EC_D}} - w_{ENV_D} \cdot \frac{Z_{ENVD}}{maxZ_{ENVD}} \tag{37}$$

Subject to: (24)-(35)

And finally, the evaluation model would be:

$Max\ Z_C$

Subject to: (19)-(20)

$$QS_{cfm}^{ht}, WM_{cm}^{ht}, U_{cm}^{t} \qquad CONTINUOUS \tag{38}$$

4 Application to the La Plata Tomato SC

The proposed collaborative tool is validated through its application to the case study of the production of different tomato varieties in La Plata region of Argentina. The SC consists of ten farms and two markets and commercializes three tomato varieties (round, pear, and cherry) with a shelf-life of two weeks [1].

To show the functioning of the designed tool, it is tested for the case where equal relative weight is given to all objectives. That is, 33% is assigned to profit maximization, waste minimization and minimization of unsatisfied demand in the case of the centralized and evaluation models, and 50% is assigned to profit maximization and waste minimization in the case of the distributed model.

The first block of Fig. 3 (Centralized) shows the range of area to be planted for each tomato variety and in each planting period. These ranges are determined by the minimum and maximum proportion of area obtained by the centralized model for these cases. These values are employed in the distributed models as an input.

The second block of Fig. 3 (Distributed) shows in addition to the recommended area range for each tomato variety and planting period (green), the proportion of area that farmers have decided to plant independently (yellow) and which is obtained after running the distributed model for the ten farmers and aggregating the results obtained. In addition, the aggregated results of the profits and waste that farmers expect to obtain by making their decision in a distributed way are displayed. To obtain these values, the profits and wastage that each farmer expects to obtain after running the distributed model were added together.

As for the proportion of area planted with each crop and in each planting period, these coincide in all the farms, this being the mix that optimizes the objectives set. In this case, all farmers decide to plant the maximum recommended area ratio with round and pear tomatoes, because they offer the highest economic margin. In the case of cherry tomatoes, only the minimum recommended area ratio is planted. As for the planting periods, it is shown that in some of them it is decided not to plant, while in others the minimum recommended, the maximum recommended, or an area between these two values is planted. The farmers expect to obtain more than seven million euros due to the sale of the entire harvest, which means that there will be no waste.

However, after the evaluation of the distributed decisions, it can be seen in the results presented in the third block of Fig. 3 (Real results) that the real profits of the SC are much lower than expected, also suffering an increase in waste and the generation of unmet demand. This is because supply and demand for crops are still not fully balanced.

To test the advantages of using the collaborative tool versus not using it, the real results previously shown are compared with those obtained by not using the collaborative tool. To do this the distributed model is used considering that the minimum and maximum proportion area to be planted are zero and one respectively in all cases, and then results are aggregated and assessed with the evaluation model.

Fig. 3. Collaborative tool application and results.

Fig. 4 compares the proportion of the total area planted with each type of tomato by farmers according to the distributed models and the real economic (SC profit), environmental (waste), and social (unmet demand) outcomes for the SC after evaluation of the distributed decisions for the cases where the collaboration tool is and is not used.

In the case of not using the collaborative tool, farmers decide independently to plant only the tomato variety that was the most profitable in the previous year, in this case, the round tomato. In contrast, when using the collaborative tool, farmers decide to plant all three tomato varieties respecting the areas recommended by the tool and planting more of those varieties that are more profitable.

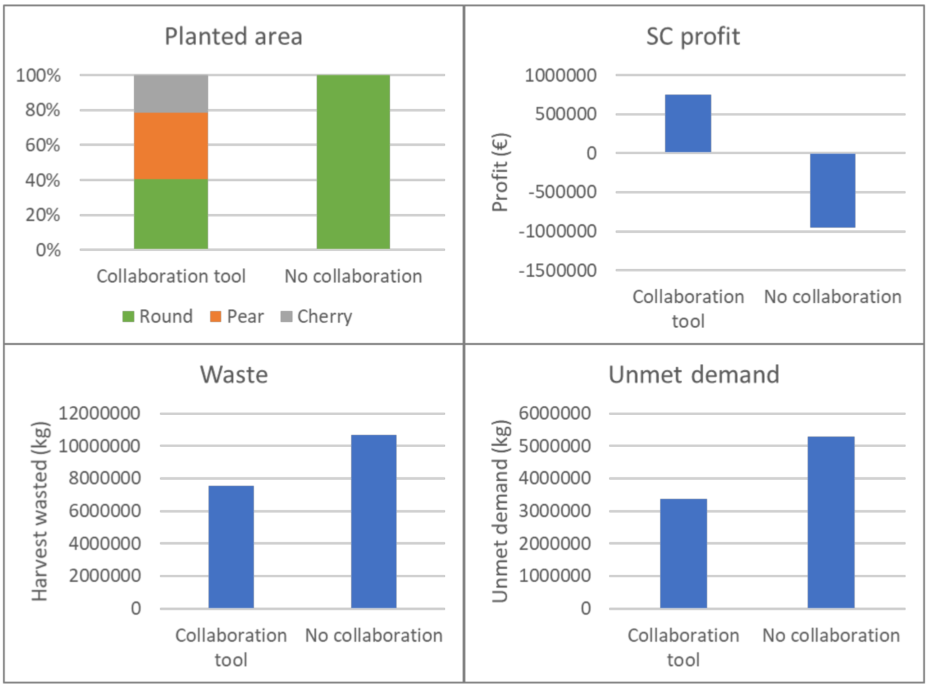

Fig. 4. Comparation of SC results using the collaboration tool or not.

When assessing the impact of these decisions on the SC by not using the collaborative tool, the chain suffers large economic losses due to the costs of planting, storing, and transporting round tomatoes that cannot be sold because there is not enough demand. This causes the wastage of a large quantity of tomatoes. Also, the entire demand for pear and cherry tomatoes cannot be met since they are not produced, being represented as unmet demand.

On the contrary, when the collaborative tool is used, a better balance between demand and supply is achieved. This has a positive impact on the sustainability of the SC economically, environmentally, and socially. Thus, farmers already benefit economically from their decisions while maintaining their independence in decision-making, and tomato waste and unmet demand are reduced.

4.1 Computational efficiency

The optimization program MPL Modeling System® Release 5.0.8.116 with the solver Gurobi Optimization 9.1.1 has been used to implement and solve the proposed models in a computer with two processors Intel® Xeon® CPU E5-2640 v2

@ 2.00 GHz 2.00 GHz, an installed capacity of 32 GB and a 64-bit operating system. In addition, databases created in Microsoft Access Database have been used both to import the input data for the models and to export the values obtained for the decision variables.

Table 3 shows the size and resolution time of the models for the presented case study. Given that the distributed models are run once per farmer up to a total of ten runs, the lowest and highest resolution time is shown for these models.

Table 4. Computational efficiency.

Scenario	Model	Constraints	Continuous variables	Binary variables	Resolution time (seconds)
Collaboration tool	Centralized	16658	20696	390	1.45
	Distributed	1590	1956	39	0.10 - 0.17
	Evaluation	708	1104	-	0.06
No collaboration	Distributed	1558	1956	39	0.12 – 0.25
	Evaluation	708	1104	-	0.07

5 Conclusions and Future Research

In this paper, a collaborative tool based on optimization models has been proposed that allows farmers to individually plan the planting, harvesting and distribution of crops by providing a better balance between crop supply and demand than that obtained when farmers make decisions completely independently (without the collaborative tool). A model has also been proposed to evaluate the performance of the decisions made by farmers when using or not using the collaborative tool.

The results show that by using the proposed tool, more crops are planted, and the sustainability of the SC is increased due to increased profits (economic aspect), reduced waste (environmental aspect) and reduced unsatisfied demand for crops (social aspect).

In the future, the proposed collaborative tool could be extended by using different artificial intelligence algorithms such as reinforcement learning to establish the minimum and maximum proportion of area to be planted with each crop and the minimum and maximum proportion of area to be planted in each planting period. In this way, through an iterative process, it would be possible to better adjust these ratios to achieve a better balance between supply and demand, while maintaining individuality in the farmers' decision-making.

On the other hand, the proposed tool has been used for the case where equal weight is assigned to the three objectives (maximising profit, minimising waste, and minimising unsatisfied demand). In future work, a sensitivity analysis could be carried out on the weights assigned to the objectives and the impact this has on the plannings obtained by the tool.

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