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Collaborative Plan to Reduce Inequalities among the Farms through Optimization

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Abstract. The crop planning problem consists in defining the crop and acreage to be planted at each farm. There are several centralized mathematical programming models to support crop planning in literature. However, centralized solutions often produce economic unfairness among the members of the supply chain, being especially relevant among the farmers in the agri-food sector. To solve it, this paper tries to answer the following research question: is it possible to reduce inequalities among the farmers through a collaborative plan? A centralized multi-objective mathematical programming model to support crop planning and the next decisions up to the sale of vegetables through a collaborative plan is proposed to answer this question. To show the validity of the proposed collaborative plan, results obtained are compared against those obtained without collaboration. The analysis of results shows that inequalities among the supply chain members can be highly reduced in a centralized decision-making approach by implementing the proposed collaborative plan, reducing a bit the supply chain profit.

Keywords: agri-food supply chain, crop planning, collaboration, optimization.

1 Introduction

Farmers decide what crops to plant at their farms and the acreage dedicated to each of the selected crops through the crop planning process [1]. The mathematical programming has proved its validity to support the crop planning process [2, 3]. Proof of this is the large number of models to support the crop planning in the literature (e.g. [4–7]). However, most of these models propose centralized approaches in which one single user makes decisions for the entire supply chain (SC).

Centralized decisions lead to the best solution for the SC, however, it produces inequalities in the profits perceived by each SC member, leading to the unwillingness to cooperate among them [8]. Farmers are often the most vulnerable actors in the chain because they tend to have fewer business-related skills, however collaboration can be used to improve their results [9]. In view of given situation, this paper tries to answer the following research question: Is it possible to reduce inequalities among the farmers through a collaborative plan?

To answer this question, a multi-objective mathematical programming model to support the crop planning problem through a collaborative plan is proposed. Its results are compared to the equivalent model not considering the collaborative plan. This model not only defines the crop planning but anticipates decisions related to the harvest, storage, distribution, sale, and clearance sale of vegetables. It considers two objectives: the maximization of SC profits, and the minimization of the unfairness among farmers.

The proposed collaborative plan is based on the three dimensions of collaboration: information sharing, decision synchronization, and incentive alignment [10]. The information on the demand for each vegetable and the available area for planting is shared with all members of the SC and each of them is assigned the demand that should satisfy according to its available area. Decisions are synchronized since a centralized model is used that simultaneously plans the planting, harvesting, storage, and distribution of vegetables. An incentive alignment is carried out since, with the sharing of demand, risks are redistributed among all members of the SC. In addition, by minimizing the unfairness among farmers, the benefits obtained are also shared.

Therefore, the contributions of this paper are the proposal of a new collaborative plan to reduce the inequalities among farmers, the mathematical modelling of the distribution of information among the members of the supply chain, and the modelling of the possibility of clearing vegetables at retailers to reduce waste.

The rest of the paper is structured as follows. Section 2 describes the problem under study and the proposed collaborative plan. Section 3 formulates the multi-objective model to support the crop planning with the established collaborative plan. Section 4 implements the model and applies it to the Argentinean tomato case study, identifying the effect of implementing the proposed collaborative plan. Finally, Section 5 outlines the main conclusions and future research lines.

2 Problem Description

This proposal focuses on the crop planning problem which consists in selecting the crops to be planted in a farm and the area allocated to each selected crop [1]. To balance the supply and demand of vegetables at markets it is necessary to anticipate the impact that such crop planning will have on the production and distribution of vegetables [11].

Because of that, this paper focuses on an entire SC and on processes carried out from the planting of vegetable plants to their sale to end consumers. The SC under study is composed of farms, cooperatives, and retailers (Fig. 1), and commercializes vegetables with an annual planting (such as tomatoes or peppers), which shelf life is limited.

Farmers are responsible for the planting and harvest of vegetables, their storage, and their transport to the cooperative with which the farm is associated. Farms can only be associated with one cooperative. Farmers can also waste vegetables when their shelf life is consumed, being the vegetables unfit for human consumption. Cooperatives act as a consolidator of vegetables received by their associated farms. Therefore, cooperatives can store vegetables, transport them to retailers, or waste them in case they deteriorate. Finally, retailers sell the vegetables received to end consumers. Storage is not allowed at retailers to avoid the need of collecting the fresh vegetables from shelves at the end of each day, store them in a refrigerated warehouse located at the retailer, and putting back vegetables on their shelves at the beginning of the next day. In this way, fresher vegetables are sold to consumers, and costs related to the refrigerated warehouse and laboring dedicated to those handling tasks are avoided. Therefore, all vegetables available at retailers should be sold in the same period of their arrival. Otherwise, vegetables should be wasted. To facilitate the sale of the oversupply of vegetables and reduce the waste that can be generated at this point, it is possible to clear some vegetables at a lower price.

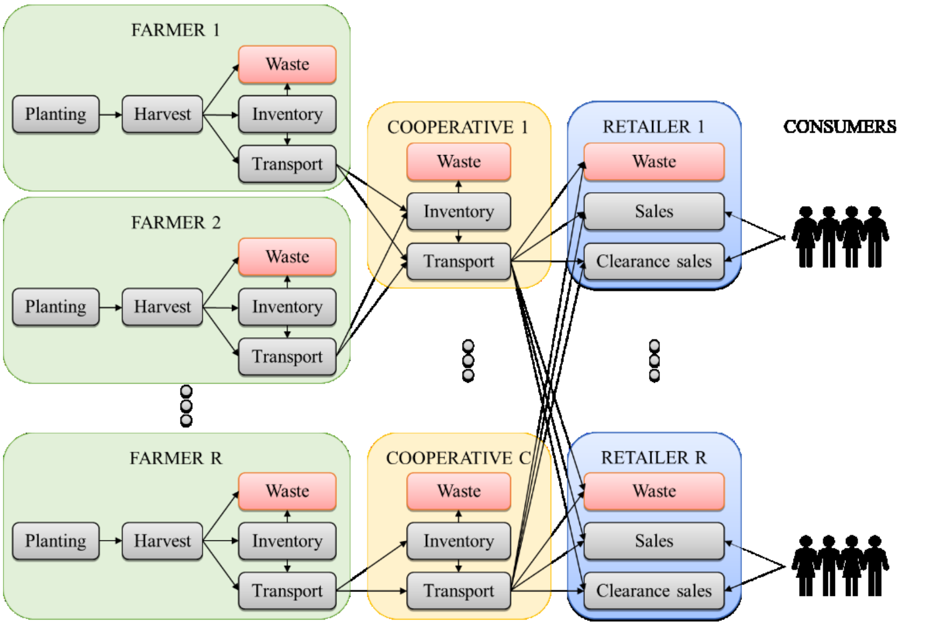

Fig. 1. SC configuration and decisions.

In this paper, we also propose to establish a collaborative plan between the different levels of the SC, being the main contribution of this paper. This collaborative plan is based on minimum information sharing, and more concretely the sharing of the demand for each vegetable and of the area available for planting at each location. In this way, retailers share the information on their demand for each vegetable among the cooperatives in such a way that the demand is distributed among cooperatives according to the total area of farmers affiliated with the cooperative. Once cooperatives know the demand for each vegetable that they should meet, they break down said demand among their members according to their areas. So, the demand for each vegetable is distributed among the SC members according to their available area for planting (Fig. 2) with the aim of adjusting the supply to the demand as much as possible, and reduce inequalities among the members of the supply chain.

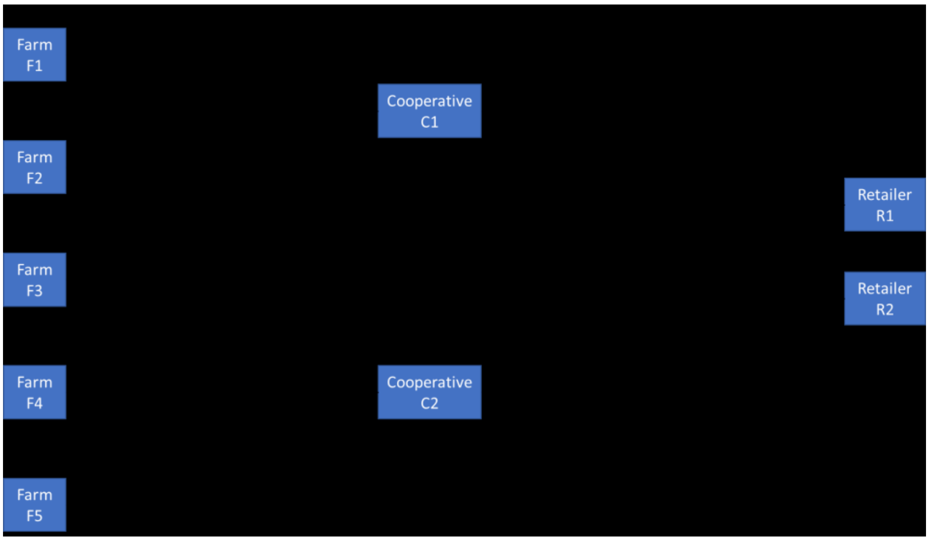

Fig. 2. Distribution of demand with the collaborative plan.

In exchange, cooperatives agree to buy from farms a minimum quantity of vegetables equivalent to 90% of the demand assigned to them, and a maximum quantity equivalent to 110% of the demand. Similarly, retailers commit to buy from cooperatives a number of vegetables ranged between 90% and 110% of their assigned demand. Note that these percentages are set as an example and their values could be modified according to the agreement reached by the members of the SC.

This collaborative plan is expected to offer several benefits to the SC: i) demand is distributed among all SC members ensuring that all of them will at least partially use their facilities and will sell vegetables to the next SC level; ii) as demand is distributed according to the areas of the SC members, economic unfairness among farms is expected to be reduced; iii) all this will make farms feel a lower economic risk when planting, being more inclined to implement the crop planning centrally defined.

3 Multi-Objective Model Formulation

Table 1 exposes the nomenclature used to formulate the model, where f refers to farms, c to farms cooperatives, r to retailers, v to vegetables, p to planting periods, h to harvest periods, t to time periods comprising the planning horizon, FC_c to the set of farms f belonging to the cooperative c, P_v to the set of planting periods p in which vegetables v can be planted, and PH_{vp} to the set of harvest periods h in which vegetables v planted in period p can be harvested.

Table 1. Nomenclature.

Parameters	
ap_f	Available area for planting in farm f
ac_c	Available area for planting in all farms belonging to cooperative c
am_v	Minimum area to be planted with vegetable v when it is decided to plant it
y_v^{ph}	Yield of vegetable v planted at p and harvested at h
de_{vr}^t	End consumers' demand of vegetable v at retailer r at period t
e_{vr}^t	Percentage of demand of vegetable v that can be sold at retailer r at a clearance sale price at period t
mdc_c	Percentage of demand that farms should meet when serving cooperative.
Mdc_c	Percentage of demand that farms can oversupply when serving cooperative.
mdr_r	Percentage of demand that cooperatives should meet when serving retailers.
Mdr_r	Percentage of demand that cooperatives can oversupply when serving retailers.
sp_{vc}^t	Selling price of one kg of vegetable v to cooperative c at period t
mp_{vr}^t	Market price of one kg of vegetable v at retailer r at period t
gp_{vr}^t	Clearance sale price of one kg of vegetable v at retailer r at period t
uc_{vr}^t	Penalty cost for not meeting one kg of vegetable v demand at retailer r at period t
wc_v^t	Penalty cost for wasting one kg of vegetable v at period t
pc_v	Planting, cultivation, and harvest cost per hectare planted with vegetable v
tcf_{vfc}	Cost of transporting one kg of vegetable v from farm f to cooperative c
tcc_{vcr}	Cost of transporting one kg of vegetable v from cooperative c to retailer r
hc_v	Holding cost for vegetable v
sl_v	Shelf life of vegetable v after harvest
msl_v	Minimum required shelf life of vegetable v at sale
ml_v	Minimum service level for each vegetable v
Decision variables	
A_{vf}^p	Area planted in farm f with vegetable v at planting period p
H_{vf}^h	Quantity of vegetable v harvested at farm f in period h
IF_{vf}^{ht}	Quantity of vegetable v harvested at farm f in period h stored at period t
WF_{vf}^{ht}	Quantity of vegetable v harvested at farm f in period h wasted at period t
TF_{vfc}^{ht}	Quantity of vegetable v harvested at farm f in period h transported to cooperative c at period t
DF_{vfc}^t	Demand of vegetable v at cooperative c that should be met by farm f in period t
IC_{vc}^{ht}	Quantity of vegetable v harvested in period h stored at period t at cooperative c
WC_{vc}^{ht}	Quantity of vegetable v harvested in period h wasted at period t at cooperative c
TC_{vcr}^{ht}	Quantity of vegetable v harvested in period h transported from cooperative c to retailer r at period t
DC_{vcr}^t	Demand of vegetable v at retailer r that should be met by cooperative c in period t
WR_{vr}^{ht}	Quantity of vegetable v harvested in period h wasted at period t at retailer r
S_{vr}^{ht}	Quantity of vegetable v harvested in period h sold at retailer r at period t
G_{vr}^{ht}	Quantity of vegetable v harvested in period h cleared at retailer r at period t
B_{vr}^t	Quantity of unmet demand of vegetable v at retailer r at period t
D_f	Difference between the region and farm f margin per area (absolute value)
YP_{vf}^p	Binary variable that takes value equal to one when farm f plant vegetable v at period p

2.1 Objectives

The model takes into account two objectives: the maximization of the SC profits, and the minimization of the economic unfairness perceived by farmers.

SC profits (Z_E) are composed of sales, clearance of vegetables, costs related to the planting, cultivation, and harvest of vegetables, their storage and transport between the nodes of the SC, and economic penalties for waste and unmet demand. In this way, this objective is not only promoting the economic sustainability of the SC, but also the environmental and social sustainability by including penalties for waste and unmet demand respectively, thus promoting their reduction (1).

$$Z_E = \sum_v \sum_r \sum_h \sum_t S_{vr}^{ht} \cdot mp_{vr}^t + \sum_v \sum_r \sum_h \sum_t G_{vr}^{ht} \cdot gp_{vr}^t - \sum_v \sum_f \sum_{p \in P_v} A_{vf}^p \cdot pc_v - \sum_v \sum_f \sum_h \sum_t IF_{vf}^{ht} \cdot hc_v - \sum_v \sum_c \sum_h \sum_t IC_{vc}^{ht} \cdot hc_v - \sum_v \sum_f \sum_c \sum_h \sum_t TF_{vfc}^{ht} \cdot tcf_{vfc} - \sum_v \sum_c \sum_r \sum_h \sum_t TC_{vcr}^{ht} \cdot tcc_{vcr} - \sum_v \sum_f \sum_h \sum_t WF_{vf}^{ht} \cdot wc_c^t - \sum_v \sum_c \sum_h \sum_t WC_{vc}^{ht} \cdot wc_c^t - \sum_v \sum_r \sum_h \sum_t WR_{vr}^{ht} \cdot wc_c^t - \sum_v \sum_r \sum_t B_{vr}^t \cdot uc_{vr}^t \ . \tag{1}$$

The perception of economic unfairness among farms (Z_U) is calculated as the difference in absolute value of the margin per hectare obtained by farm and the average margin per hectare obtained by all farmers (2). PF_f indicates the margin obtained by farm f and is calculated as the difference of the sale of vegetables to cooperatives and costs related to planting, cultivation and harvest of vegetables, their transport to cooperatives, and the penalty for waste in the farm (3)

$$Z_U = \sum_f \left| \frac{PF_f}{ap_f} - \frac{\sum_f PF_f}{\sum_f ap_f} \right| . \tag{2}$$

$$PF_f = \sum_v \sum_c \sum_h \sum_t TF_{vfc}^{ht} \cdot \left(sp_{vc}^t - tcf_{vfc} \right) - \sum_v \sum_{p \in P_v} A_{vf}^p \cdot pc_v - \sum_v \sum_h \sum_t IF_{vf}^{ht} \cdot hc_v - \sum_v \sum_h \sum_t WF_{vf}^{ht} \cdot wc_c^t \qquad \forall f \ . \tag{3}$$

2.2 Constraints

The model is subjected to the following constraints. The area planted with all vegetables throughout the planning horizon at each farm cannot exceed its available area (4).

$$\sum_v \sum_{p \in P_v} A_{vf}^p \leq ap_f \qquad \forall f \ . \tag{4}$$

Due to technical reasons, a minimum area should be planted for each vegetable when it is decided to do so (5), and the maximum area is limited to the available area at farm.

$$YP_{vf}^p \cdot am_v \leq A_{vf}^p \leq YP_{vf}^p \cdot ap_f \qquad \forall v, f, p \in P_v \ . \tag{5}$$

The quantity of vegetables to be harvested depends on the planted area and the yield of plants (6). It is assumed that all matured vegetables at the plant should be harvested.

$$H_{vf}^h = \sum_{p \in PH_{vp}} A_{vf}^p \cdot y_v^{ph} \qquad \forall v, f, h \ . \tag{6}$$

Once harvested, vegetables can be stored at farm, transported to cooperative, or wasted (7). Vegetables can be stored until their remaining shelf life gets lower than the required by consumers (8). Thus, the inventory for vegetables with lower remaining shelf lives should be equal to zero (9).

$$IF_{vf}^{ht} = H_{vf}^{h} - \sum_c TF_{vfc}^{ht} - WF_{vf}^{ht} \qquad \forall v, f, h, t = h\ . \tag{7}$$

$$IF_{vf}^{ht} = IF_{vf}^{ht-1} - \sum_c TF_{vfc}^{ht} - WF_{vf}^{ht} \quad \forall v, f, h, h < t \leq h + sl_v - msl_v\ . \tag{8}$$

$$IF_{vf}^{ht} = 0 \qquad \forall v, f, h, t \geq h + sl_v - msl_v \tag{9}$$

Each farm should transport to the cooperative a quantity of vegetable within the range agreed with the cooperative (10). This forces all farms to plant all vegetables.

$$DF_{vfc}^{t} \cdot mdc_c \leq \sum_{h \leq t} TF_{vfc}^{ht} \leq DF_{vfc}^{t} \cdot Mdc_c \qquad \forall v, c, f \in FC_c, t\ . \tag{10}$$

Once vegetables arrive to cooperatives can be stored, transported to retailer, or wasted (11). Vegetables can be stored until their remaining shelf life gets lower than the required by consumers (12)

$$IC_{vc}^{ht} = IC_{vc}^{ht-1} + \sum_f TF_{vfc}^{ht} - \sum_r TC_{vcr}^{ht} - WC_{vc}^{ht} \tag{11}$$
$$\forall v, c, h, h \leq t \leq h + sl_v - msl_v\ .$$

$$IC_{vc}^{ht} = 0 \qquad \forall v, f, h, t \geq h + sl_v - msl_v \tag{12}$$

Each cooperative should transport to retailers a quantity of vegetable within the range agreed with the retailer (13).

$$DC_{vcr}^{t} \cdot mdr_r \leq \sum_{h \leq t} TC_{vcr}^{ht} \leq DC_{vcr}^{t} \cdot Mdr_r \qquad \forall v, c, r, t\ . \tag{13}$$

Once vegetables reach the retailer, it must be sold in the same period of its arrival. If there is an excess of supply, vegetables can be cleared or wasted (14).

$$\sum_c TC_{vcr}^{ht} = S_{vr}^{ht} + G_{vr}^{ht} + WR_{vr}^{ht} \qquad \forall v, r, h, h \leq t \leq h + sl_v - msl_v\ . \tag{14}$$

The quantity of vegetables to be cleared is limited by a percentage of demand (15).

$$\sum_{h \leq t} G_{vr}^{ht} \leq e_{vr}^{t} \cdot de_{vr}^{t} \qquad \forall v, r, t\ . \tag{15}$$

If there is not enough vegetable at retailer to meet demand, unmet demand is produced (16).

$$\sum_{h \leq t} S_{vr}^{ht} + B_{vr}^{t} = de_{vr}^{t} \qquad \forall v, r, t\ . \tag{16}$$

A minimum service level should be met at each retailer in the planning horizon (17).

$$\sum_h \sum_{\substack{t \geq h \\ t \leq h + sl_v - msl_v}} S_{vr}^{ht} \geq \sum_t ml_v \cdot de_{vr}^{t} \qquad \forall v, r\ . \tag{17}$$

Retailer distributes its demand between cooperatives according to the available area of the farms belonging to cooperatives (18).

$$DC_{vcr}^{t} = \frac{de_{vr}^{t} \cdot ac_c}{\sum_c ac_c} \qquad \forall v, c, r, t\ . \tag{18}$$

Cooperatives distributes its assigned demand between farms belonging to the cooperative according to the available area for planting at each farm (19).

$$DF_{vfc}^{t} = \frac{\sum_r DC_{vcr}^{t} \cdot ap_f}{ac_c} \qquad \forall v, c, f \in FC_c, t\ . \tag{19}$$

The nature of decision variables is defined (20).

$$\begin{array}{ll} A_{vf}^{p}, H_{vf}^{h}, IF_{vf}^{ht}, WF_{vf}^{ht}, TF_{vfc}^{ht}, DF_{vfc}^{t}, IC_{vc}^{ht}, WC_{vc}^{ht}, & \\ TC_{vcr}^{ht}, DC_{vc}^{rt}, WR_{vr}^{ht}, S_{vr}^{ht}, G_{vr}^{ht}, B_{vr}^{t} & CONTINUOUS \\ Y_{vt}, YP_{vf}^{p} & BINARY \end{array} . \tag{20}$$

3.3 Resolution Methodology

Equation (2), which corresponds to the minimization of economic unfairness perceived by farmers, should be linearized. To do this, it is replaced by equations (21)-(23), in which the variable D_f, that represents the unfairness perceived by the farmer, is forced to acquire the absolute value for the difference between the margin per hectare obtained by the farmer and the average margin per hectare obtained by all farmers.

$$Z_U = \sum_f D_f\ . \tag{21}$$

$$D_f \geq \frac{PF_f}{ap_f} - \frac{\sum_f PF_f}{\sum_f ap_f} \qquad \forall f\ . \tag{22}$$

$$D_f \geq \frac{\sum_f PF_f}{\sum_f ap_f} - \frac{PF_f}{ap_f} \qquad \forall f\ . \tag{23}$$

The weighted sum method is used to solve the multi-objective model. Through this method weights are distributed among the objectives ensuring that the weight assigned to all of them adds up to one ($w_E + w_U = 1$). In addition, the values for the objectives need to be scaled to acquire values between zero and one. For that, each objective is divided by an estimation of the highest value they can acquire (MZ_E for objective Z_E, and MZ_U for objective Z_U). The multi-objective model used to carry out experimentation is:

$$Max\ Z = w_E \cdot \frac{Z_E}{MZ_E} - w_U \cdot \frac{Z_U}{MZ_U}\ . \tag{24}$$

subject to:
(1), (3), (4)-(23)

3 Application to the Argentinean Tomato Case Study

The model is validated through its application to the Argentinean Tomato Case Study extracted from [12], in which ten farms from La Plata region in Argentina should decide the crop planning for three types of tomato: round, pear, and cherry. Farms are grouped into two cooperatives and one retailer is considered. Demand and prices for the three types of tomato are obtained from the Buenos Aires Central Market webpage (www.mercadocentral.gob.ar/). The planning horizon is composed of 52 weeks, which is equivalent to one year. The calendar for the planting and harvest of plants is shared by the three types of tomato and is displayed in Fig. 3.

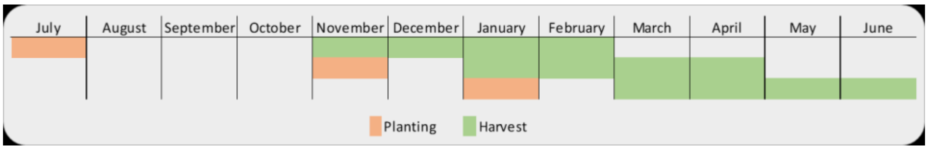

Fig. 3. Planting/Harvest calendar.

Through the collaborative plan, it is considered that farmers should serve the cooperatives an amount of product that represents between 90 and 110% of the assigned demand for each type of tomato. The same happens between cooperatives and retailers so that cooperatives must serve between 90 and 110% of the demand for each type of tomato assigned to them by the retailers.

The proposed model is solved for six scenarios characterized by different distribution of weights between the objectives: maximization of profits and minimization of economic unfairness among farms (set CPP). These same scenarios are executed for a situation in which the proposed collaborative plan is not considered (set NCP). For that, constraints (10), (13), (18), and (19) are avoided.

The solutions for all sets and scenarios are compared in terms of SC profits, economic unfairness perceived by farms, the percentage of harvest wasted, and the percentage of unmet demand (Fig. 4).

The results show that the scenarios in which the collaborative plan is implemented obtain less SC profits chain than when the collaborative plan is not implemented. However, SC profits are reduced between 12% and 22%, being this acceptable if other indicators, such as the unfairness perception by farms, are highly improved.

In fact, in those scenarios in which the weight assigned to the objective of minimizing the economic unfairness between farms is ranged between 0% and 60%, it is observed that, when applying the collaborative plan, the economic unfairness among farms can be drastically reduced. In this way, reducing the economic unfairness perceived by farms from 90% to 95% only implies a worsening of the SC profits by approximately 20%.

These results are of great interest since the reduction of unfairness makes the members of the SC more involved when implementing the crop planning obtained centrally. On the contrary, trying to implement a crop planning obtained centrally without a collaborative plan provides great unfairness among the SC members and can cause some of these members, usually the most disadvantaged, not to jointly participate in the crop planning but to take their individual decisions. This would be a great inconvenience for the entire SC, which would see its profits diminished due to the imbalance between supply and demand generated by farmers who individually decide their crop planning without taking into account the rest of the members of the chain.

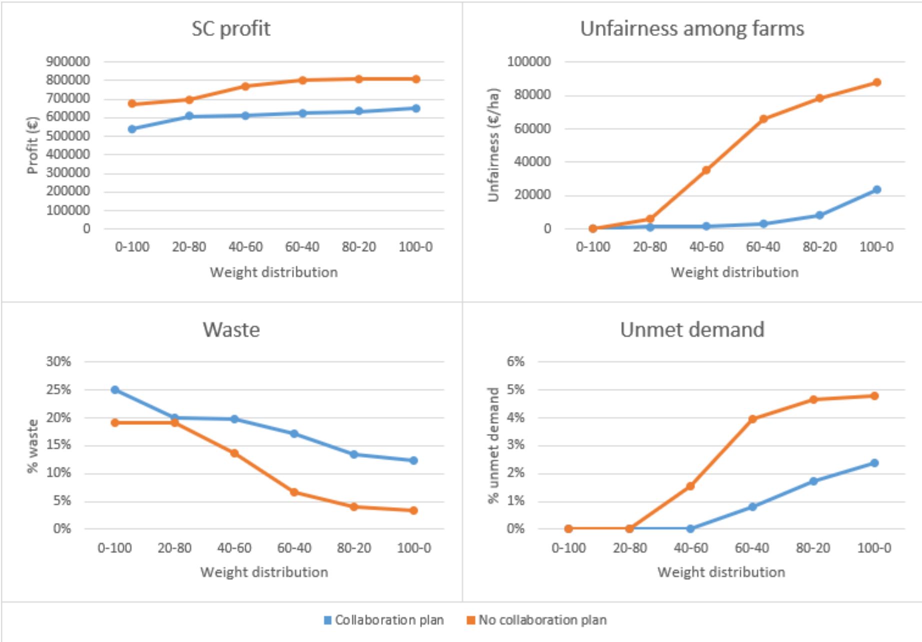

Fig. 4. Results for the SC profits, unfairness among farms, waste, and unmet demand.

On the other hand, the impact of implementing the collaborative plan can be observed on environmental aspects, such as the percentage of harvest wasted along with the SC, and social aspects, such as the percentage of unmet demand (in addition to the unfairness among farms). In this sense, waste increases between 1 and 10% when implementing the collaborative plan, while the unmet demand is reduced by up to 100%. This is because, when implementing the collaborative plan, an average of two more hectares are planted in all scenarios, thus obtaining more vegetables that are dedicated to serving such demand. As the pattern followed by the plant's yield is not similar to the patterns of demand, a surplus of vegetables is generated in some of the periods, thus causing such waste.

The proposed model was implemented in MPL 5.0.8.116 and solved by using the Gurobi™ 9.1.1 solver in an Intel® Core™ i7-7500U CPU @ 2.70 GHz 2.90 GHz with an installed RAM of 8.00 GB and a 64-bits operative system. The computational efficiency for the scenarios and the average resolution time is displayed in Table 2.

Table 2. Computational efficiency.

Scenario	Constraints	Continuous variables	Binary variables	Resolution time
CPP	194,371	25,271	90	1.4 seconds
NCP	187,195	23,399	90	0.7 seconds

4 Conclusions and Future Research Lines

This paper proposes a multi-objective mathematical programming model to centrally define the crop planning of an agri-food SC while implementing a collaborative plan to reduce the economic unfairness perceived by farmers. Results obtained by this model are compared with the ones of an equivalent centralized model not considering the collaborative plan. Results are compared in terms of SC profits, economic unfairness among farms, percentage of harvest wasted, and percentage of unmet demand for six scenarios characterized by different weight distribution between objectives.

Results show that implementing the collaborative plan would highly reduce the unfairness perceived by farmers while reducing the SC profits. Implementing the proposed collaborative plan can therefore be very beneficial for agri-food SC since it allows drastically reducing the unfairness perception of its members without this supposing a great economic loss for the SC. This reduction in the unfairness makes farmers more willing to collaborate and to implement the crop planning obtained, thus avoiding the main problem of centralized models.

This study could be extended in future works by introducing the uncertainty inherent to the agri-food sector in parameters such as the shelf life of vegetables, their demand, and prices, or the costs associated with their production and distribution.

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