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Increasing the Sustainability of a Fresh Vegetables Supply Chain Through the Optimization of Funding Programs: A Multi-Objective Mathematical Programming Approach

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Abstract:

Purpose: This research develops a model to improve the quality and freshness of sold vegetables through a funding program between farmers and retailers. Through this program, retailers who are interested in the distribution of first quality vegetables provide funds to farmers to increase their production this type of vegetables through the acquisition of new machinery, technology, or training.

Design/methodology/approach: The problem is solved through a multi-objective mathematical programming model that simultaneously optimizes the supply chain profits, the waste of vegetables, the economic unfairness among farmers, the unfairness in the distribution of funds, and the freshness of sold vegetables. The ε-constraint method is used to obtain several non-dominated solutions to the problem after linearizing the non-lineal equations related to the unfairness objectives.

Findings: Results show that it is possible to improve the indicators related to the vegetable waste, the economic unfairness, the unfairness in the distribution of funds and the freshness of vegetables while maintaining similar to optimal profits for the supply chain. Interesting trade-offs between the five objectives are identified, which can be used by supply chain members to select the most appropriate solution to be implemented in the real supply chain.

Originality/value: This research models aspects relevant to the agri-food sector that have not been previously modelled for the problem under study. The main novelties of this paper are the consideration of the limited shelf life of the vegetables as well as the requirement of ensuring a minimum freshness at the moment of their sale, the price dependence on the quality and freshness of vegetables, the optimization of vegetable waste and the freshness of vegetables sold, as well as the joint optimization of the five previously defined objectives..

Keywords: agri-food, perishability, quality, unfairness, collaboration, optimization, multi-objective

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1. Introduction

Vegetable consumers are becoming more selective and demanding with regard to the freshness and quality of vegetables (Correia & Rola-Rubzen, 2012; Surucu-Balci & Tuna, 2021). In this context, several authors maintain that the proportion of first quality vegetables to be obtained from harvest can be increased through the acquisition of new machineries, technologies, and the training of farmers in new cultivation and harvesting techniques (Wahyudin, Sutopo, Hisjam, Yuniaristanto & Kurniawan, 2015).

However, many farmers do not have the needed financial and material resources to carry out this type of investment. This problem is widespread among small farmers with plantation areas of less than two hectares, who are responsible for the 80% of the world's agricultural production (Lowder, Skoet & Raney, 2016). As a solution, some authors propose to create a collaboration program between retailers, who have greater purchasing power, and farmers (Sutopo, Hisjam, & Yuniaristanto, 2012). Through this collaborative program, retailers offer financial support to farmers with a commitment that the latter will use this funding to increase the proportion of first quality vegetables to be harvested from their fields.

Although these proposals found in the literature offer a possible solution to the end consumers' requirement for high quality vegetables, they do not consider that consumers additionally require the vegetables to be as fresh as possible. In fact, consumers might be unwilling to buy vegetables that do not meet their expectations in terms of freshness (Esteso, Alemany, & Ortiz, 2021). This makes it necessary to propose new solutions incorporating, in addition to the quality aspects already covered in the literature, information on shelf life and freshness of vegetables.

To fill this gap, this paper proposes a novel multi-objective mathematical programming model to sustainably increase the quality and freshness of vegetables through a funding program. In order to incorporate the freshness of vegetables, the minimum freshness requirement of consumers is modelled on the one hand, and the dependence of vegetables prices on freshness and quality of vegetables is modelled on the other hand. All these modelled elements are novelties of this paper.

In addition, to offer economically, environmentally, and socially sustainable solutions, the proposed model simultaneously optimizes five objectives that are shown to be in conflict: supply chain profits (economic), vegetables waste (environmental), economic unfairness among farmers (social), unfairness in the distribution of funds (social), and freshness of sold vegetables (social). The joint optimization of these five objectives is another novelty of this paper.

Note that two objectives related to the unfairness among farmers are included in the model. This is because the proposed model supports centralized decision-making whereby a single decision-maker makes decisions that all members of the supply chain must implement and respect (Esteso, Alemany, Ortiz & Liu, 2021). Centralized decision-making offers advantages such as obtaining the best economic solutions for the entire supply chain, but on the other hand it may generate losses for some members of the chain and large profits for others (Stadtler, 2009). Similarly, such inequalities in the results obtained by members of the supply chain will also occur when other non-economic objectives are optimised centrally. In this context, the members of the supply chain may interpret these inequalities in their results as an unfairness. The perception of this unfairness may lead the members of the supply chain to act on their own to obtain better individual results, to the detriment of the overall outcome of the supply chain (Alemany, Esteso, Ortiz & del Pino, 2020). Therefore, the model minimizes the economic unfairness between farmers understood as the difference between the margin per hectare obtained by the farmer and the average margin per hectare obtained by all farmers, and the unfairness in the distribution of funds understood as the different between the number of funds received by a farmer and the average number of funds received by all farmers.

To solve the multi-objective model, the ε-constraint method (Mavrotas, 2009) is used to obtain several non-dominated solutions for a specific case study. These solutions are then analysed to find trade-offs between the considered objectives that may be of interest to the supply chain from the managerial point of view. In addition, a section on managerial insights is included where the different uses of the model as a decision support tool are discussed.

Therefore, the objective of this paper is threefold: i) to propose a novel multi-objective mathematical programming model to sustainably increase the freshness and quality of vegetables through a funding program, ii) to validate the proposed model through its application to a case study, and iii) to show how managers can use the proposed model to support decision making in other agri-food supply chains that face similar problems.

The rest of the paper is structured as follows. Section 2 analyses previous mathematical programming models proposing a funding program to increase the quantity of first quality products harvested and commercializes in the supply chain. Section 3 describes the problem under study. Section 4 formulates the multi-objective model to distribute retailers' funds among farms considering the freshness of sold products and proposes its resolution methodology. Section 5 analyses the obtained non-dominated solutions. Finally, Section 6 outlines conclusions and future research lines.

2. Literature Review

This section analyses the existing mathematical programming models proposing a funding program between retailers and farmers to increase the proportion of first quality vegetables to be obtained from harvest. Note that it is not intended to give in-depth details of the analysed models, but rather those features that are most relevant to the problem under study in order to show its originality.

Therefore, the models found in literature were analysed in terms of the members of the supply chain that participate in the funding program, the product characteristics considered by the model (perishability and quality), the dependence of prices on such product characteristics (Table 1), and the objectives optimized by the models (Table 2). To facilitate comparison with the existing literature, the last row of each table shows the features modelled by the model proposed in this paper.

In order to carry out this analysis, it is first necessary to define the concepts of perishability and quality of agri-food products.

The term perishability is defined as the decay, damage, dryness, spoilage, evaporation, deterioration, obsolescence, loss of utility, or loss of marginal value of a product that results in decreasing usefulness compared to the fresh one (Bajegani & Gholamian, 2020; Wee, 1993). Therefore, the perishability of products with limited shelf life is related to their freshness, which is represented in this paper by the remaining shelf life of the product and calculated as the difference between the shelf life of a product at the time of harvesting and the time elapsed since harvesting (Grillo, Alemany, Ortiz & Fuertes-Miquel, 2017).

With regard to quality, the Food and Agriculture Organization (FAO) of the United Nations recognises that there are different notions of the term quality in agri-food products, its two basic notions being: (i) a statement of characteristics that determine that a thing is what it is in relation to the purpose of its use, and (ii) an expression of a level of excellence, a form of distinction from similar things, which justifies its pursuit (FAO, 2004).

In line with the first notion proposed by the FAO, many authors define agri-food product quality as the result of an objective and subjective evaluation of the intrinsic characteristics of the product (Sloof, Tijskens, & Wilkinson, 1996), such as its colour, taste, size, ripeness and consistency among others (Buche, Cuq, Fortin, & Sipieter, 2019; Ha & Jang, 2010), that influence the degree of consumer acceptance of that product (Wang & Li, 2012).

On the other hand, other authors such as Grillo et al. (2017) define the quality of agri-food products as the existing product categories according to the degree of defects or damage that each product unit presents. According to this definition, products that do not have defects or damage would be recognised as excellent, being aligned to the second notion of the FAO, which would justify the preference in their acquisition by some consumers, as well as the payment of higher prices for their purchase. This quality category is usually printed on the product packaging (as a label or certification), being a static factor during the marketing of the product (Fernández-Zarza, Amaya-Corchuelo, Belletti & Aguilar-Criado, 2021). In this paper, products are classified into different quality categories according to these latter definitions.

Authors	Funding program			Product characteristic		Price dependence	
	F	C	R	Q	P	Q	P
Sutopo, Hisjam and Yuniaristanto (2011)	X		X	X		X	
Sutopo et al. (2012)	X		X	X		X	
Sutopo, Hisjam and Yuniaristanto (2013a)	X		X	X		X	
Sutopo, Hisjam and Yuniaristanto (2013b)	X		X	X		X	
Sutopo, Hisjam, Yuniaristanto and Kurniawan (2013)	X		X	X		X	
Wahyudin et al. (2015)	X		X	X		X	
Esteso, Alemany, Ortiz and Guyon (2018)	X		X	X		X	
Esteso, Alemany and Ortiz (2020)	X		X	X		X	
Esteso, Alemany, Ortiz and Zaraté (2020)	X	X	X	X		X	
This paper	**X**	**X**	**X**	**X**	**X**	**X**	**X**

F: Farmers, C: Cooperatives, R: Retailers; Q: Quality, P: Perishability

Table 1. Literature review (Part I)

Most models set up a funding program in which retailers select with farmer(s) to invest in with the objective of maximizing supply chain profits. In this way, they invest in those farmers who then send them products for distribution, thereby increasing the quantity of first quality products they can sell to markets and hence their profits. However, these approaches do not take into account the role of the farmers' cooperatives in the supply chain and in the distribution of funds. This detail was first modelled by Esteso, Alemany, Ortiz et al. (2020) who proposed four mathematical programming models for distributing funding among farmers according to different criteria (directly proportional to farm areas or inversely proportional to the first quality production of farms) and objectives (supply chain profits, economic unfairness among farmers, investment unfairness). These authors assumed that the cooperatives were responsible for collecting all the funds offered by the retailers and distributing them among their farmer members. However, although in this paper cooperatives are not in charge of distributing retailers' funds to farmers, they play an important role in the distribution of first quality products among retailers (a retailer might therefore not receive product from the farmer in which it has invested) and therefore in the functioning of the funding program.

Regarding the products characteristics considered by each of the models, it is shown that all models consider only the quality of the products. In this way, they make a distinction between first and second quality products or high- and low-quality products. However, none of the papers analysed take into account the perishability of the products whereby their shelf life decreases over time. This paper fills this gap by modelling that the products have a limited shelf-life after harvest that decreases over time, and that the customers require a minimum freshness of the product (minimum remaining shelf life) at the time of sale.

Since previous models only considered product quality, they modelled that the prices of products in the markets were dependent on their quality, leaving aside other important aspects of the agri-food sector such as the relation between prices and the freshness of the products. This aspect has been modelled in this paper in which prices are not only dependent on the quality of the products but also vary depending on the freshness of the products (the fresher the product, the higher the price).

Finally, and as mentioned above, most of the models analysed take all their decisions with the objective of maximizing the agri-food supply chain profits. On the other hand, Esteso, Alemany, Ortiz et al. (2020) proposed several models for the distribution of funds, two of them being multi-objective models that optimized two objectives simultaneously: supply chain profits and economic unfairness among farmers, or supply chain profits and unfairness in the distribution of funds. Therefore, a model that simultaneously optimizes all three objectives has not been considered so far. In this paper, not only these three objectives are simultaneously modelled, but also include two new objectives which are the minimization of waste in the supply chain and the maximization of the freshness of products at the time of sale, thus filling another gap in literature.

Therefore, the main novelties of this paper are: i) modelling of the limited shelf life of products, ii) modelling of the requirement for minimum freshness of products at the time of sale, iii) modelling of the price dependence on freshness and quality of products, iv) minimization of the waste generated along the supply chain, v) maximization of the freshness of products at the time of sale, and vi) joint optimization of the supply chain profits, waste generated, economic unfairness among farmers, unfairness in the distribution of funds, and freshness of sold vegetables.

	Objective				
Authors	Max. Supply chain profit	Min. Waste	Min. Economic unfairness among farmers	Min. Unfairness in the distribution of funds	Max. Freshness of sold vegetables
Sutopo et al. (2011)	X				
Sutopo et al. (2012)	X				
Sutopo, Hisjam and Yuniaristanto (2013a)	X				
Sutopo, Hisjam and Yuniaristanto (2013b)	X				
Sutopo, Hisjam, Yuniaristanto et al. (2013)	X				
Wahyudin et al. (2015)	X				
Esteso et al. (2018)	X				
Esteso, Alemany and Ortiz (2020)	X				
Esteso, Alemany, Ortiz et al. (2020)	X		X	X	
This paper	**X**	**X**	**X**	**X**	**X**

Table 2. Literature review (Part II)

3. Problem Description

The supply chain under study is responsible for the production and distribution of multiple perishable vegetables with limited shelf-life. The shelf life of this vegetables is predetermined and once it has elapsed, the vegetable becomes worthless (Alemany, Esteso, Ortiz, Hernández, Fernández, Garrido et al., 2021). The considered supply chain is composed by farmers, cooperatives, retailers, and markets, who represent the demand of end consumers (Figure 1).

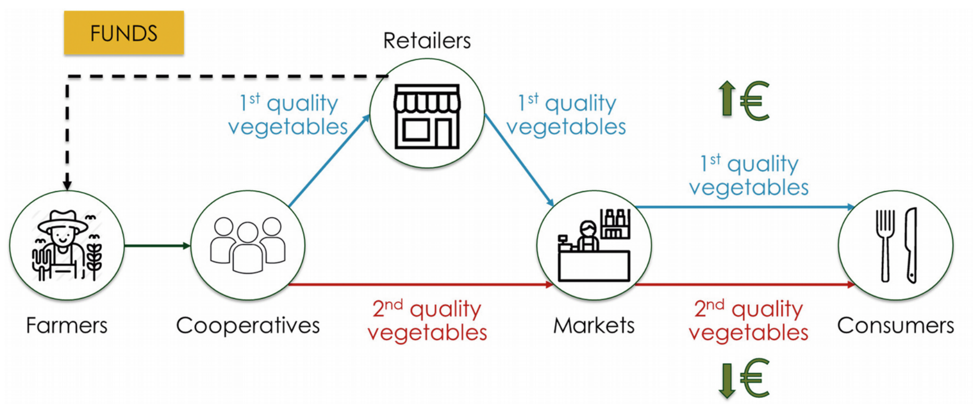

Figure 1. Agri-food supply chain under study

Farmers are responsible for the cultivation and harvest of vegetables that are assumed to have been previously planted. For this purpose, farmers know the harvesting calendar for the different vegetables planted as well as the area planted with each of the vegetables. Once the farmers harvest the vegetables, they must sort the vegetables according to their quality into first or second quality vegetables. The proportion of harvested vegetables that are first or second quality on each farm depends on the skill level of their farmers. Once sorted, vegetables can be stored at farms until their shelf-life is consumed or transported to the cooperative to which the farmer belong.

The cooperatives are in charge of the distribution of the vegetables to the retailers. These retailers are only interested in commercializing first quality vegetables. Thus, to avoid wasting second quality vegetables, the retailers transport the second quality vegetables directly to the markets, where they are sold at a lower price than the first quality vegetables.

Retailers transport the first quality vegetables to the markets, where vegetables are finally sold to the end consumers in order to meet their demand. In this context, retailers can fund farmers to increase the proportion of first quality vegetables to be obtained from harvest through the acquisition of new machineries, technologies, and the training in new cultivation and harvesting techniques (Wahyudin et al., 2015). In this funding program, each retailer has a limited budget for this type of investments. In addition, farmers are classified into different levels according to their skills. Farmers pass from one to the following skill level with each fund perceived. Each farmer can perceive a maximum number of funds. It is therefore assumed that with each fund received, farmers increase the proportion of first quality vegetables.

In addition, the commercialized vegetables are perishable, what means that their shelf-life decreases as time passed between their harvest and sale. Vegetables should have a minimum remaining shelf-life at the time of their sale to ensure a minimum freshness to end consumers. In addition, the price of vegetables is dependent not only on the quality of the vegetable sold but also on its freshness at the time of sale. Due to the perishability of vegetables and the minimum freshness required by customers, wastes can appear along the supply chain. Despite this possibility, in the problem under study it is not allowed to waste vegetables in non-farmers nodes of the supply chain, forcing that only those vegetables that will be sold in the markets respecting the minimum freshness required by the customers can be transported between the nodes of the chain. Therefore, it is assumed that in case the minimum freshness cannot be assured, vegetables are wasted at the farming level avoiding unnecessary distribution costs and gas emissions of transport activities, simultaneously contributing to the economic and environmental pillars of sustainability.

4. Multi-objective Model Formulation

The nomenclature used to formulate the model to solve the above problem is defined in Table 3.

Indices	
v	Vegetable ($v = 1, \ldots, V$)
q	Quality of vegetables ($q = 1, \ldots, Q$)
f	Farmer ($f = 1, \ldots, F$)
c	Farmer cooperative ($c = 1, \ldots, C$)
r	Retailer ($r = 1, \ldots, R$)
m	Market ($m = 1, \ldots, M$)
t	Period of time ($t = 1, \ldots, T$)
h	Harvest period ($h = 1, \ldots, H$)
x	Freshness of vegetables ($x = 1, \ldots, X$)
Set of indices	
FC_{fc}	Set of farmers f belonging to a cooperative c

Parameters	
a_f	Area of farm f (ha).
s_f^{vh}	Quantity of vegetable v harvested in farm f at harvest period h (kg).
g_f^{vh}	Proportion of first quality vegetable v harvested by farm f at harvest period h (dimensionless).
sl^v	Shelf-life of vegetable v after harvest (day).
msl^v	Minimum shelf-life that vegetable v needs to have to be sold (day).
sp_c^{vqt}	Unitary income for selling vegetable v with quality q to cooperative c at period t (€/kg).
cp_f^v	Unitary cost for producing vegetable v at farm f (€/kg).
ci_f^{vt}	Unitary cost for storing vegetable v at farm f at period t (€/kg).
ctc_{fc}^{vt}	Unitary cost for transporting v from farm f to cooperative c at period t (€/kg).
ctr_{cr}^{vt}	Unitary cost for transporting v from cooperative c to retailer r at period t (€/kg).
ctm_{rm}^{vt}	Unitary cost for transporting v from retailer r to market m at period t (€/kg).
ctd_{cm}^{vt}	Unitary cost for transporting v from cooperative c to market m at period t (€/kg).
p_m^{vqxt}	Unitary price for vegetable v with quality q and freshness x at market m at period t (where $x = t - h$) (€/kg).
up_m^{vqt}	Unitary penalty cost for not meeting demand of vegetable v with quality q at market m at period t (€/kg).
de_m^{vqt}	Demand of vegetable v with quality q at market m at period t (kg).
l_f	Initial skill level of farm f (level).
cf	Cost of increasing one skill level (€/level).
β	Improvement of the first quality vegetable proportion per skill level (dimensionless).
N	Number of skill levels (level).
b_r	Budget of retailer r for funding (€).
Decision variables	
QH_f^{vqh}	Quantity of vegetable v with quality q harvested at farm f at harvest period h (kg).
Inv_f^{vqht}	Inventory of vegetable v with quality q harvested at farm f at harvest period h stored at period t (kg).
QC_{fc}^{vqht}	Quantity of vegetable v with quality q harvested at farm f at harvest period h transported to cooperative c at period t (kg).
QR_{cr}^{vqht}	Quantity of vegetable v with quality q harvested at harvest period h transported from cooperative c to retailer r at period t (kg).
QM_{rm}^{vqht}	Quantity of vegetable v with quality q harvested at harvest period h transported from retailer r to market m at period t (kg).
QD_{cm}^{vqht}	Quantity of vegetable v with quality q harvested at harvest period h transported from cooperative c to market m at period t (kg).
W_f^{vqht}	Quantity of vegetable v with quality q harvested at farm f at harvest period h wasted at period t (kg).
QS_m^{vqht}	Quantity of vegetable v with quality q harvested at harvest period h sold at market m at period t (kg).
UD_m^{vqt}	Unmet demand of vegetable v with quality q at market m at period t (kg).
CL_f	Current skill level of farm f (level).
FI_{fr}	Number of funds given by retailer r to farm f (fund).
MF_f	Margin obtained by farmer f (€).

Table 3. Nomenclature

4.1. Objective Function

The proposed multi-objective model considers five objectives aligned to the three pillars of sustainability. In terms of the economic pillar, the profits of the entire agri-food supply chain are maximized. Regarding the environmental pillar, the waste of vegetables generated along the supply chain is minimized. In respect of the social pillar, economic unfairness among farmers and the unfairness in the distribution of funds among farmers are minimized, and the freshness of vegetables sold to the end consumers is maximized.

4.1.1. Maximization of SC Profits (Z_p)

The SC profits are calculated as the difference between vegetable sales and the costs associated to the production of vegetables, their storage on farms, and their transport between the different nodes of the supply chain, the investments made by retailers, and penalty costs related to unmet demand (1).

$$\begin{aligned} Max\ Z_P = \sum_{v=1}^{V}\sum_{q=1}^{Q}\sum_{h=1}^{H}\Bigg(&\sum_{m=1}^{M}\sum_{t=h}^{h+sl^v-msl^v}\sum_{x=t-h}^{t-h} p_m^{vqxt}\cdot QS_m^{vqht} - \sum_{f=1}^{F} cp_f^v \cdot QH_f^{vqh} \\ &- \sum_{f=1}^{F}\sum_{t=h}^{h+sl^v-msl^v} ci_f^{vt}\cdot Inv_f^{vqht} - \sum_{f=1}^{F}\sum_{c\in FC_{fc}}^{C}\sum_{t=h}^{h+sl^v-msl^v} ctc_{fc}^{vt}\cdot QC_{fc}^{vqht} \\ &- \sum_{c=1}^{C}\sum_{r=1}^{R}\sum_{t=h}^{h+sl^v-msl^v} ctr_{cr}^{vt}\cdot QR_{cr}^{vqht} - \sum_{c=1}^{C}\sum_{m=1}^{M}\sum_{t=h}^{h+sl^v-msl^v} ctd_{cm}^{vt}\cdot QD_{cm}^{vqht} \\ &- \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{t=h}^{h+sl^v-msl^v} ctm_{rm}^{vt}\cdot QM_{rm}^{vqht}\Bigg) - \sum_{m=1}^{M}\sum_{v=1}^{V}\sum_{q=1}^{Q}\sum_{t=h}^{T} up_m^{vqt}\cdot UD_m^{vqt} \\ &- \sum_{f=1}^{F}\sum_{r=1}^{R} FI_{fr}\cdot cf \end{aligned} \tag{1}$$

4.1.2. **Minimization of Waste (Z_W)**

Waste is produced when vegetables perish (2). In this case, it is assumed that vegetables will only be wasted on the farm level since farmers will only send vegetables to cooperatives (and these to retailers and markets) if there is sufficient demand to absorb the supply of vegetables. Otherwise, the farmers waste the excess vegetables that remain in storage on their premises, thus avoiding costs and gas emissions related to the distribution of vegetables that cannot be sold.

$$Min\ Z_W = \sum_{f=1}^{F}\sum_{v=1}^{V}\sum_{q=1}^{Q}\sum_{h=1}^{H}\sum_{t=h}^{h+sl^v-msl^v} W_f^{vqht} \tag{2}$$

4.1.3. **Minimization of Economic Unfairness Among Farmers (Z_{EU})**

The economic unfairness among farmers is calculated as the absolute difference between the margin per hectare obtained by each farm and the mean margin per hectare for all farms (3). The margin is composed by sales of vegetables to cooperatives, and costs related to the production, storage, and distribution of vegetables from the farm to the cooperatives (4).

$$Min\ Z_{EU} = \sum_{f=1}^{F}\left|\frac{MF_f}{a_f} - \frac{\sum_{f=1}^{F} MF_f}{\sum_{f=1}^{F} a_f}\right| \tag{3}$$

$$MF_f = \sum_{v=1}^{V}\sum_{q=1}^{Q}\sum_{h=1}^{H}\left(\sum_{c=1}^{C}\sum_{t=h}^{h+sl^v-msl^v}\left(sp_c^{vqt} - ctc_{fc}^{vt}\right)\cdot QC_{fc}^{vqht} - cp_f^v \cdot QH_f^{vqh} - \sum_{t=h}^{h+sl^v-msl^v} ci_f^{vt}\cdot Inv_f^{vqht}\right) \tag{4}$$

4.1.4. **Minimization of the Unfairness in the Distribution of Funds (Z_{FU})**

The unfairness in the distribution of funds is calculated as the absolute difference between the number of funds received by each farm and the average number of funds received by all farms (5).

$$Min\ Z_{FU} = \sum_{f=1}^{F}\left|\sum_{r=1}^{R} FI_{fr} - \frac{\sum_{f=1}^{F}\sum_{r=1}^{R} FI_{fr}}{\sum_{r=1}^{R} b_r/cf}\right| \tag{5}$$

4.1.5. **Maximization of Freshness of Sold Vegetables (Z_{FR})**

The average freshness of sold vegetables should be calculated as the quantity of vegetables sold multiplied by their shelf life at the moment of sale divided by the quantity of vegetables sold. A strict calculation of the average freshness would imply solving a non-linear model, which would complicate its resolution. To avoid this non-linear equation, this model uses the linear approximation to the calculation of average freshness proposed by Grillo et al. (2017) in which the quantity of vegetables sold in the denominator is replaced by the demand of vegetables (6). These authors showed the validity to use this approximation by proving the equivalence between both objective functions.

$$Max\ Z_{FR} = \frac{\sum_{m=1}^{M}\sum_{v=1}^{V}\sum_{q=1}^{Q}\sum_{h=1}^{H}\sum_{t=h}^{h+sl^v-msl^v}(sl^v + h - t)\cdot QS_m^{vqht}}{\sum_{m=1}^{M}\sum_{v=1}^{V}\sum_{q=1}^{Q}\sum_{t=1}^{T} dem_m^{vqt}} \tag{6}$$

4.2. **Constraints**

The model is subjected to the following constraints. Vegetables that are ready to be harvested in a certain harvesting period must be harvested and sorted according to their quality (7). It is not possible to decide to leave ripe vegetables in the plant until the next harvesting period.

$$s_f^{vh} = \sum_{q=1}^{Q} QH_f^{vqh} \qquad \forall f, v, h \tag{7}$$

The quantity of first quality vegetables (q = 1) is calculated by multiplying the quantity of vegetables ready for harvest by the initial proportion of first quality vegetables produced at the farm plus the improvement of such proportion through received funds (8). The rest of harvested vegetables are considered second quality vegetables (9).

$$QH_f^{vqh} = s_f^{vh}\cdot\left(g_f^{vh} + \beta\cdot CL_f\right) \qquad \forall f, v, q = 1, h \tag{8}$$

$$QH_f^{vqh} = s_f^{vh}\cdot\left(1 - g_f^{vh} - \beta\cdot CL_f\right) \qquad \forall f, v, q = 2, h \tag{9}$$

Once harvested, the vegetables can be stored on the farmer's premises or transported to the cooperatives (10-11). In addition, the shelf life of the vegetables must be taken into account so that the vegetables are wasted when their freshness (or remaining shelf life) is less than the minimum required by the final consumers (12).

$$Inv_f^{vqht} = QH_f^{vqh} - \sum_{c=1}^{C} QC_{fc}^{vqht} - W_f^{vqht} \qquad \forall f, v, q, h, t = h \tag{10}$$

$$Inv_f^{vqht} = Inv_f^{vqht-1} - \sum_{c=1}^{C} QC_{fc}^{vqht} - W_f^{vqht} \quad \forall f, v, q, h, h < t \leq h + sl^v - msl^v \tag{11}$$

$$Inv_f^{vqht} = 0 \qquad \forall f, v, q, h, t \geq h + sl^v - msl^v \tag{12}$$

Farmers transport both first and second quality vegetables to the cooperative to which they belong. The cooperatives then transport the first quality vegetables to the retailers and the second quality vegetables to the markets. Since it is not possible to store vegetables in the cooperatives, it is ensured that the quantity of first quality vegetables received by a cooperative from all farms is equal to the quantity of first quality vegetables transported from the same cooperative to all retailers (13). In the same way, all second quality vegetables received by a cooperative must be transported to the markets (14).

$$\sum_{f=1}^{F} QC_{fc}^{vqht} = \sum_{r=1}^{R} QR_{cr}^{vqht} \qquad \forall c, v, q = 1, h, h \leq t \leq h + sl^v - msl^v \tag{13}$$

$$\sum_{f=1}^{F} QC_{fc}^{vqht} = \sum_{m=1}^{M} QD_{cm}^{vqht} \qquad \forall c, v, q = 2, h, h \leq t \leq h + sl^v - msl^v \tag{14}$$

Similarly, since it is not possible to store vegetables in the retailers, they distribute the vegetables received from the cooperatives to the markets in the same period of their reception (15).

$$\sum_{c=1}^{C} QR_{cr}^{vqht} = \sum_{m=1}^{M} QM_{rm}^{vqht} \qquad \forall r, v, q, h, h \leq t \leq h + sl^v - msl^v \tag{15}$$

Since the transport of second quality vegetables from cooperatives to retailers and from retailers to markets is not allowed, constraint (16) ensures that the quantity of second quality vegetables transported between the nodes is zero. Similarly, first quality vegetables cannot be transported from cooperatives to markets so the quantity of first quality vegetables transported between these nodes is set to zero (17).

$$\sum_{r=1}^{R}\sum_{v=1}^{V}\sum_{h=1}^{H}\sum_{t=h}^{h+sl^v-msl^v} \left(\sum_{c=1}^{C} QR_{cr}^{vqht} + \sum_{m=1}^{M} QM_{rm}^{vqht} \right) = 0 \qquad \forall q = 2 \tag{16}$$

$$\sum_{c=1}^{C}\sum_{m=1}^{M}\sum_{v=1}^{V}\sum_{h=1}^{H}\sum_{t=h}^{h+sl^v-msl^v} QD_{cm}^{vqht} = 0 \qquad \forall q = 1 \tag{17}$$

Vegetables that arrive to markets from retailers and cooperatives are finally sold to end consumers (18). In case there is not enough supply to meet demand, unmet demand would be generated (19).

$$\sum_{r=1}^{R} QM_{rm}^{vqht} + \sum_{c=1}^{C} QD_{cm}^{vqht} = QS_m^{vqht} \qquad \forall m, v, q, h, h \leq t \leq h + sl^v - msl^v \tag{18}$$

$$\sum_{h=1}^{t} QS_m^{vqht} + UD_m^{vqt} = de_m^{vqt} \qquad \forall m, v, q, t \tag{19}$$

As regards the system for distributing funds among farmers, the skill level of farmers is equal to their initial skill level plus the levels improved with retailer funds and cannot exceed the maximum level defined in the funding program (20).

$$CL_f = l_f + \sum_{r=1}^{R} FI_{fr} \leq N \qquad \forall f \tag{20}$$

On the other hand, it should be ensured that the proportion of first quality vegetables obtained at each farm is lower or equal to the unit (21).

$$g_f^{vh} + \beta \cdot CL_f \leq 1 \qquad \forall f, v, h \tag{21}$$

In addition, investments made by retailers to fund farmers cannot exceed the budget set by retailers for this purpose (22).

$$\sum_{f=1}^{F} FI_{fr} \cdot cf \leq b_r \qquad \forall r \tag{22}$$

Finally, constraint (23) shows the nature of decision variables of the model.

$$\begin{array}{ll} QH_f^{vqh}, Inv_f^{vqht}, W_f^{vqht}, QC_{fc}^{vqht}, QR_{cr}^{vqht}, QD_{cm}^{vqht}, & CONTINUOUS \\ QM_{rm}^{vqht}, QM_{rm}^{vqht}, QS_m^{vqht}, UD_m^{vqt} & \\ FI_{fr}, CL_f & INTEGER \end{array} \tag{23}$$

4.3. Resolution Methodology

To solve the proposed model, it is necessary to first linearize the non-linear equations comprising the objectives Z_{EU} (minimization of economic unfairness among farmers) and Z_{FU} (minimization of unfairness in the distribution of funds). To linearize these expressions, variables EU_f and FU_f are created to represent the absolute differences related to objectives Z_{EU} and Z_{FU}, respectively (24-25).

$$Min\ Z_{EU} = \sum_{f=1}^{F} EU_f \tag{24}$$

$$Min\ Z_{FU} = \sum_{f=1}^{F} FU_f \tag{25}$$

Variable EU_f is calculated as the absolute difference between the margin per hectare per farm and the average margin per hectare of the whole farming region. Constraints (26-27) are formulated to linearly ensure the variable EU_f to acquire absolute values. This same process is made to variable FU_f representing the absolute difference between funds received by each farmer and the average funds received by farms (28-29).

$$EU_f \geq \frac{MF_f}{a_f} - \frac{\sum_{f=1}^{F} MF_f}{\sum_{f=1}^{F} a_f} \qquad \forall f \tag{26}$$

$$EU_f \geq \frac{\sum_{f=1}^{F} MF_f}{\sum_{f=1}^{F} a_f} - \frac{MF_f}{a_f} \qquad \forall f \tag{27}$$

$$FU_f \geq \sum_{r=1}^{R} FI_{fr} - \frac{\sum_{f=1}^{F}\sum_{r=1}^{R} FI_{fr}}{\sum_{r=1}^{R} b_r/cf} \qquad \forall f \tag{28}$$

$$FU_f \geq \frac{\sum_{f=1}^{F}\sum_{r=1}^{R} FI_{fr}}{\sum_{r=1}^{R} b_r/cf} - \sum_{r=1}^{R} FI_{fr} \qquad \forall f \tag{29}$$

Once objectives are linearized, the ε-constraint method is applied to solve the model. This method transforms the multi-objective model into a single-objective model by selecting one objective as the objective function and transforming the rest of objectives into constraints (Mavrotas, 2009). In this case, the maximization of supply chain profits is maintained as the model's objective function (30) while the minimization of waste (31), the minimization of economic unfairness among farmers (32), the minimization of unfairness in the distribution of funds (33), and the maximization of freshness of sold vegetables (34) are transformed into constraints of the model. The new model is formulated as follows:

$$Max\ Z_P \tag{30}$$

subject to:

$$\sum_{f=1}^{F}\sum_{v=1}^{V}\sum_{q=1}^{Q}\sum_{h=1}^{H}\sum_{t=h}^{h+sl^v-msl^v} W_f^{vqht} \leq \varepsilon_W \tag{31}$$

$$\sum_{f=1}^{F} EU_f \leq \varepsilon_{EU} \tag{32}$$

$$\sum_{f=1}^{F} FU_f \leq \varepsilon_{FU} \tag{33}$$

$$\frac{\sum_{m=1}^{M}\sum_{v=1}^{V}\sum_{q=1}^{Q}\sum_{h=1}^{H}\sum_{t=h}^{h+sl^v-msl^v}(sl^v + h - t)\cdot QS_m^{vqht}}{\sum_{m=1}^{M}\sum_{v=1}^{V}\sum_{q=1}^{Q}\sum_{t=1}^{T} dem_m^{vqt}} \geq \varepsilon_{FR} \tag{34}$$

and Equations (4, 7-23, 26-29).

5. Experimental Design

The objective of this section is threefold: (1) to check the conflict between the considered objectives, (2) to validate the proposed multi-objective model and derive some managerial insights, and (3) to analyse the computational efficiency of its optimization.

Data used was based in the instance of data exposed in Esteso, Alemany, Ortiz et al. (2020). A four-month horizon in a daily basis was considered. The considered supply chain is composed by nine farmers, three cooperatives, one retailer, and one market. The supply chain produces and commercializes a unique vegetable whose shelf life is equal to 14 days. It is assumed that vegetables should have a minimum remaining shelf life of three days to be considered fresh. In addition, it is assumed that the prices of vegetables are dependent on the freshness of vegetables as well as on their quality and the period of time. Figure 2 shows the average price of vegetables depending on their freshness and quality.

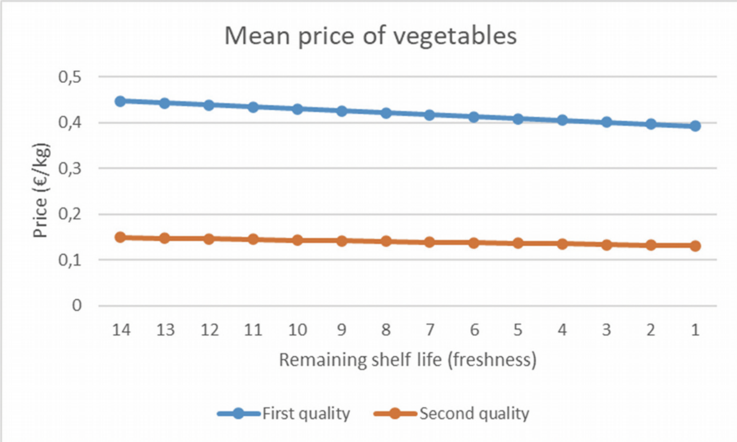

Figure 2. Mean price of vegetables according to freshness and quality

5.1. Experimental Results

To validate the proposed model, first it is verified that considered objectives are not aligned. If two or more objectives were aligned, an improvement of one of them would necessarily imply the improvement of the other, not being necessary to apply a multi-objective approach. To do this, a partial correlation analysis is performed on a set of non-dominated solutions obtained through lexicographic optimization.

Lexicographic optimization consists of sequentially optimizing the objectives by fixing the value acquired by previously optimized objectives (Mavrotas, 2009). For example, in a case with two objectives (f_1 and f_2), the objective f_1 would be optimized and later the objective f_2 would be optimized by setting the value of f_1 to its optimal value. By performing this process with all the possible sequences of the five objectives considered in this paper, a total of 120 solutions are obtained, which are refined to 40 non-dominated solutions after eliminating duplicates. The partial correlation analysis is performed on these solutions is shown in Table 3.

	Z_p	Z_W	Z_{EU}	Z_{FU}	Z_{FR}
Z_p	1				
Z_W	-0.066	1			
Z_{EU}	-0.364	-0.113	1		
Z_{FU}	-0.019	-0.958	0.203	1	
Z_{FR}	-0.660	-0.596	0.358	0.634	1

Table 3. Partial correlation analysis

For two objectives to be aligned, values greater than 0.9 should be obtained for objectives optimized in the same sense (maximization-maximization or minimization-minimization), or less than -0.9 for objectives optimised in the opposite sense (maximization-minimization). After this analysis it is shown that objectives are not aligned, and, in case of objectives Z_W and Z_{FU} (both minimized) are in conflict, so that when one of them improves the other necessarily worsens. Once it is verified that objectives are not aligned, it is possible to continue with the multi-objective proposal.

For this, the ε-constraint method previously exposed is applied. ε-values are obtained by calculating equal intervals between the objectives' minimum and maximum values obtained by the lexicographic optimization. Figure 3 shows the results for 24 non-dominated solutions in terms of supply chain profits, quantity of wasted vegetables, economic unfairness among farmers, unfairness in the distribution of funds among farmers, freshness of vegetables sold, and the percentage of unmet demand.

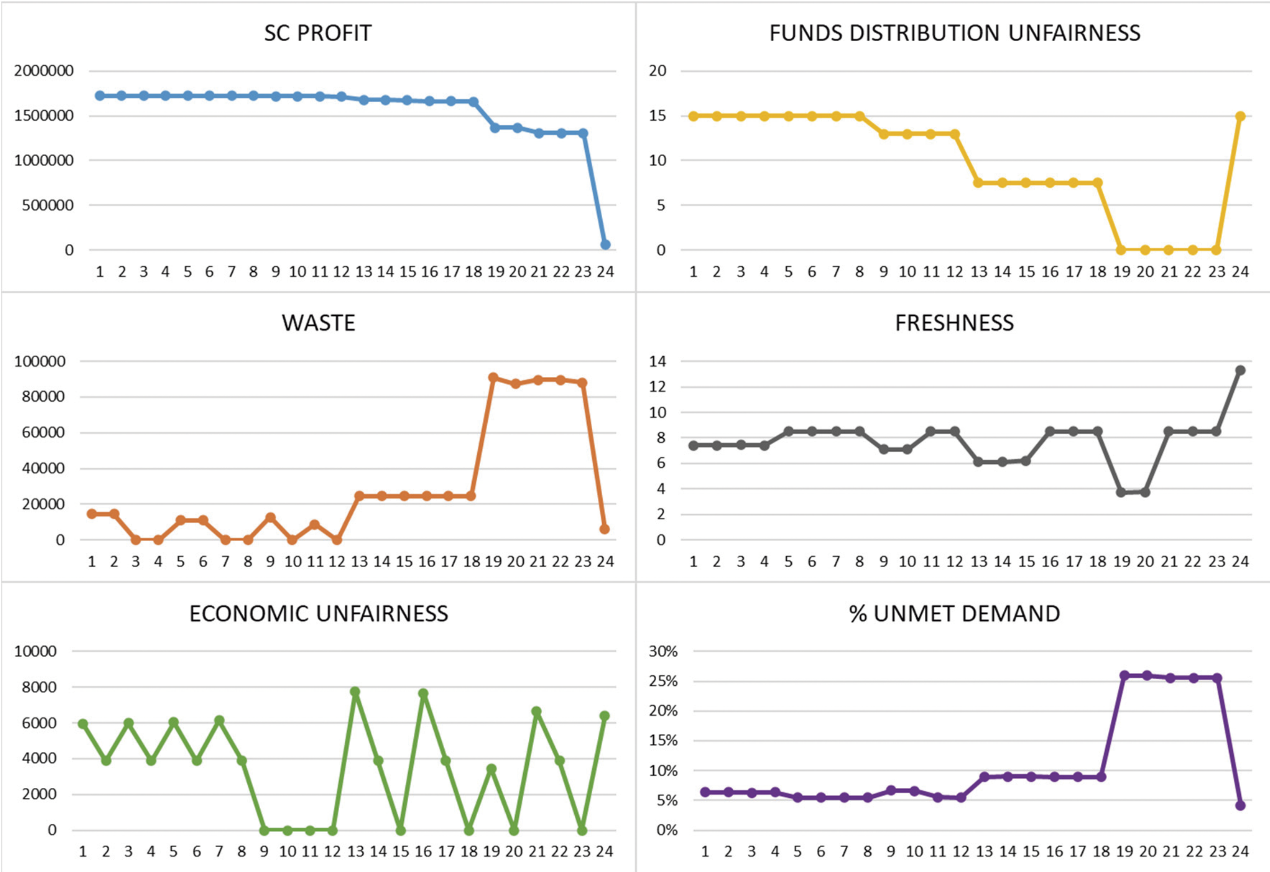

Figure 3. Non-dominated solutions for the multi-objective model

Results show that similar supply chain profits are obtained for most of the non-dominated solutions (solutions 1 to 18), showing some differences in the rest of indicators. Therefore, the members of the supply chain can analyse these solutions to select which of them best suits the interests of the supply chain according to the aspects they consider most relevant (waste, economic unfairness, unfairness in the distribution of funds, freshness of vegetables, or unmet demand) without making a big difference in the profits to be received by the supply chain.

On the other hand, it is observed that those solutions that minimize the unfairness in the distribution of funds among farmers (solutions 19 to 23) see the profits of the supply chain considerably worsened. Likewise, these solutions imply the waste of a large amount of vegetables as well as the dissatisfaction of more than 25% of the demand. Therefore, these solutions do not seem to be economically, environmentally and socially interesting for the supply chain despite eliminating the unfairness in the distribution of funds.

This is because in order to eliminate inequalities in the distribution of funds, the model chooses not to give any fund to any of the farmers and thus not to make use of the funding program. Thus, as farmers do not increase the proportion of first quality vegetables to be harvested, the supply of second quality vegetables is higher than their demand so that the entire demand for second quality vegetables can be satisfied, resulting in a large amount of second quality vegetables being wasted. At the same time, there is not enough supply of first quality vegetables to meet the demand, so the unmet demand for this type of vegetables increases considerably compared to the rest of solutions where the funding program is used.

In the case of the solution that maximizes the freshness of vegetables at the time of sale (solution 24) this implies a decrease in supply chain profits to values close to 5,000 € (equivalent to 3% of the best profit obtained with this model). This solution provides good results in terms of supply chain waste and unmet demand. However, due to the economic results it offers, it is likely that this solution would be one of the first to be rejected by members of the supply chain for its implementation.

Finally, solutions that offer better values for the economic unfairness among farmers (solutions 9 to 12) offer interesting supply chain profits close to the optimum, while offering satisfactory values for the waste, the unmet demand, and the freshness of vegetables at sale. These solutions do not have a fair distribution of funds among farmers, and this may be their main drawback for implementation. However, they could be accepted by farmers as the economic unfairness between them would be totally eliminated, thus reducing the sense of injustice and thus encouraging their collaboration in the implementation of the decisions taken.

Note that the results shown in this section and the conclusions drawn from their analysis are only valid for the data instance used in this paper. Therefore, such conclusions should not be extrapolated to other supply chains without first testing their applicability to the new data instance. To understand how to run the proposed model for other data instances and what are the main potential uses of this model as a tool to better support decision-making, see section 6. Managerial insights.

5.2. Computational Efficiency

Intel® Core™ i7-7500U CPU with a 2.70 GHz processor, and an installed capacity of 8.0 GB and a 64-bit operating system was used to solve the model. The model was implemented in the optimization software MPL® 5.0.8 and solved with the Gurobi ™ 8.1.1 solver. Microsoft Access Databases were used to store the input data and to export the valued for the decision variables. Model statistics and the average computational efficiency for the 24 executions of the model are presented in Table 4.

Continuous variables	Integer variables	Constraints	Average solution time (seconds)
98,607	18	926,230	83

Table 4. Model statistics and computational efficiency

Since the same instance of data is used to obtain the 24 non-dominated solutions, the dimension of the model is the same in all cases. Thus, the number of continuous and integer variables employed as well as the number of constraints considered is the same for all the model runs.

Regarding the execution time, it has ranged between 36 and 227 seconds in the 24 executions. It is observed that no execution has exceeded four minutes of time. The mean resolution time to obtain these non-dominated solutions was of 83 seconds. Therefore, the model presented is outlines as a support tool for quick resolution decision-making. This allows it to be used to test different scenarios that allow the analysis of "what would happen if" a decision was fixed, or some input data were changed.

6. Managerial Insights

As shown in previous sections, the proposed model has proved to be a suitable tool for decision makers to establish a funding program between farmers and retailers to improve the quality and freshness of marketed vegetables, and to plan the harvesting, storage, distribution, and sale of vegetables.

The model aims to optimize five objectives simultaneously that are aligned with the three pillars of sustainability. Obtaining several non-dominated solutions by solving the model through the ε-constraint method allows decision makers to compare the solutions obtained and find interesting trade-offs between the objectives considered (supply chain profits, waste, economic unfairness among farmers, unfairness in the distribution of funds, and freshness of sold vegetables).

The Section 5.1. has shown the process followed to solve the model and to analyse the possible trade-offs between the pillars of sustainability according to the objectives considered for a single data instance, so the conclusions drawn from this analysis are only applicable to the case study used in this paper. However, this solving and analysis procedure can be replicated by any decision maker by running the model for the corresponding input data characterizing its specific supply chain. Despite the non-dominated solutions obtained will be different from our selected case study, their trade-off analysis would be very valuable for decision makers. Indeed, they will be able to select, using some multi-criteria decision-making technique or based on their own professional experience, which non-dominated solution is the most appropriate to be implemented in the supply chain according to their interests with respect to the stated objectives and sustainability.

On the other hand, decision makers could use the model for a "what-if" analysis in order to go in-depth on what would happen if there were certain changes in the supply chain environment. For example, the decision maker might ask questions such as: what would happen if vegetable prices fluctuated? What would happen if demand grew? What if customers required vegetables with a higher freshness than the previously stated?

To analyse such "what if" situations, the decision maker should run the proposed model with the new input data reflecting the new scenarios and repeat the entire process. For instance, to analyse what if customers required vegetables with a higher freshness, the decision-maker could run the model for a data instance where the minimum freshness of the product is one week (scenario 1), for the same data instance where the minimum freshness of the vegetable is two weeks (scenario 2), and so on until all desired scenarios are represented. Once the model has been run for the defined scenarios, the results obtained could be compared between them to determine what impact a change in this element (in this case, the minimum freshness required) would have on the performance of the supply chain according to the objectives considered by the model.

In addition, decision-makers could develop a similar study for those elements considered by the model (input data) over which either they have some control or can be negotiated. The objective of this analysis would be to determine the best value to assign to these parameters in order to achieve interesting results for the supply chain. For example, by running the model for various "what-if" scenarios in which different values are assigned to the maximum budget for the funding program, the decision-maker could determine which is the most appropriate value or range of values for that parameter, thus setting the budget to be respected in subsequent runs of the model. This study could also be replicated to the other parameters of the model which are under control of the decision maker.

Finally, the model can be used as a simulation model by evaluating alternative solutions different from those obtained by the ε-constraint method, as regards all the objectives and their feasibility. For this purpose, new constraints should be included in the model to force the decision variables to take the desired value. This functionality of the model is also valuable for those decision-makers who wish to replan their decisions as the planning horizon progresses, or as some of the inputs used (demand, price, costs, etc.) are updated.

7. Conclusions

A multi-objective model to sustainably improve the quality and freshness of sold vegetables through a funding program is proposed. After checking that the proposed objectives are not aligned, the ε-constraint method is applied to solve the model and 24 non-dominated solutions are obtained.

The non-dominate solutions are analysed in terms of supply chain profits, waste generated, economic unfairness among farmers, unfairness in the distribution of funds, freshness of sold vegetables, and the percentage of unmet demand. The analysis of the results shows that it is possible to reduce waste, supply chain unfairness and unmet demand, and increase the freshness of vegetables sold while maintaining similar supply chain profits. In addition, interesting trade-offs between the objectives have been identified.

The main advantage of used centralised approach is the optimisation of outcomes for the supply chain as a whole, so that better results are obtained than could be achieved when chain members act independently. However, it has limitations. It has previously been discussed how centralization of decisions can lead to unfair results for chain members. This paper solves this problem by including two objectives that minimize the unfairness generated between chain members. Another limitation of centralized decision making is that it assumes that a single decision maker makes decisions that concern the different members of the supply chain. Thus, each member loses its individuality and decision-making power, and has to respect the decisions made centrally.

Although at first glance it may seem that chain members may be unwilling to participate in this type of decision-making, more and more chains are establishing collaborative mechanisms among their members to enjoy the benefits of centralised decision-making. Examples of this type of mechanism are the signing of contracts in which retailers commit to buy all (or part of) the crop from farmers if they respect centrally defined planting areas for each vegetable (Federgruen, Lall & Şimşek, 2019), or the use of group decision support systems to select from a number of centralised solutions which of them will be finally implemented in the company (Zaraté, Alemany, del Pino, Esteso & Camilleri, 2019).

In this article, it is assumed that supply chain members might be willing to participate in the implementation of centrally made decisions since: (i) they offer the best solutions for the supply chain as a whole, (ii) unfairness among the supply chain members are minimised, encouraging the acceptance of the centralised solution, (iii) by offering multiple non-dominated solutions, supply chain members could employ a group decision support system to select among all the solution to be implemented in the supply chain. In fact, it would be interesting to use a group decision support system to allow the supply chain members to collaboratively select which non-dominated solution they want to implement in the supply chain, thus encouraging their participation in decision-making and avoiding situations where farmers or other supply chain members act independently and thus harming the overall supply chain results.

It would be also interesting to comparatively analyse the non-dominated solution selected by the members of the real supply chain to be implemented through a group decision support system, and the solution that would be selected by a single decision maker by using some multi-criteria technique.

The proposed model could be extended in the future by modelling the uncertainty inherent to the agri-food sector. Some parameters that could be considered as uncertain are the shelf life of the products, the proportion of first quality vegetables to be obtained from harvest, or the amount by which this proportion improves with each of the funds received by farmers. Furthermore, in the case of having historical data on the values acquired by these elements, they could be modelled stochastically.

The inherent heterogeneity of the agri-food sector could also be taken into account by assuming for example that not all units of the same vegetables behave in the same way in terms of shelf life (e.g., two round tomatoes harvested on the same harvest period could have a different remaining shelf life) or that a fund does not bring the same degree of improvement in the proportion of first quality vegetable to be obtained by one farmer or another.

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