Centralized and Distributed Optimization Models for the Multi-Farmer Crop Planning Problem under Uncertainty: Application to a Fresh Tomato Argentinean Supply Chain Case Study

Imbalance between supply and demand of crops frequently occurs in markets originating an excess or shortage of supply in relation to demand. This causes high volatility and uncertainty in market prices, unmet demand, and waste, especially for fresh crops due to their limited shelf-life. This imbalance is mainly due to the inherent uncertainty present in the agricultural sector, the perishability of fresh crops, and the lack of coordination among farmers when making planting and harvesting decisions. Despite farmers usually plan the planting and harvesting in an individual way, there is a scarcity of research addressing the crop planning problem in a distributed manner and, even less, assessing their impact on the supply chain (SC) as a whole. In this paper, we developed a set of novel mathematical programming models to plan the planting and harvest of fresh tomatoes under a sustainable point of view for multi-farmer supply chains under uncertainty in different decision-making scenarios: i) distributed, ii) distributed with maximum and minimum land area constraints to be planted for each crop, iii) distributed with information sharing, and iv) centralized. Then, for each distributed scenario, the individual solution per farmer as regards the planting and harvesting decisions per crop are integrated to obtain the overall supply to satisfy the markets demand. This allows the assessment of the farmers' real performance and the impact of their individual decisions to the entire SC performance. We also compare the results obtained for each scenario with the centralized model in terms of economic, environmental, and social impact. The experimental design shows that, when integrating the solutions for the whole SC, significant differences between planned and real results are obtained in each scenario as regards the gross margin per hectare, unmet demand, waste, and unfairness between farmers, being the distributed model with information sharing the most similar to the centralized one. The results show that uncertainty consideration in models improves the gross margin and the unfairness among farmers in all scenarios for both, planned and real evaluation.

Keywords: planting; harvesting; fuzzy optimization; centralized and distributed decision-making, fresh tomato supply chain

1. Introduction

The crop planning problem consists of deciding at the beginning of each production cycle, which crops farmers are going to plant in each of their parcels (Cid-Garcia, Bravo-Lozano, & Rios-Solis, 2014) and their acreage, in case more than one crop is allowed to be planted in the same period and parcel. Farmers usually made crop planning decisions in function of the expected benefits per crop that mainly depends on the market prices which in turn are strongly influenced by the crop supply-demand balance (Tweeten & Thompson, 2009). Prices influence the behavior of both, consumers and producers, but in an opposite way: higher prices encourage more production by the producers but less consumption by the consumers, while low prices discourage production by the producers and encourage consumption by the consumers (Mani, Hudu, & Ali, 2018).

On the other hand, it is common for farmers to decide the production of each crop individually without any type of collaboration among them. This absence of coordination and the extended custom among farmers of increasing production of the most profitable crops of the previous season, lead the existence of some crops with overproduction and others with under production, causing the decrease and increase of market prices, respectively. This also provokes high discrepancies between the planned benefits of farmers and the real ones because of the unsold production. Moreover, this cyclic behaviour has also a great impact on waste and satisfied demand quantities. To balance total supply and demand, a centralized decision-making approach in a multi-farmer context can be considered. However, this approach could produce inequalities in the profits of farmers, leading to the unwillingness to cooperate among them (Stadtler, 2009) for crop planning.

In this situation, an increasing number of recent research works recognize the necessity of implementing collaboration mechanisms among the members of fruit and vegetable SCs for achieving sustainability (Prima Dania, Xing, & Amer, 2018), increase revenues and customer satisfaction and reduce the negative impact of uncertainty (Esteso, Alemany, & Ortiz, 2018). In their review, Handayati et al. (2015), identify mathematical modelling as one methodology used in agri-food supply chain coordination that has proven also its validity for the crop planning problem (Saranya and Amudha, 2017)

The complexity of matching supply and demand becomes a more difficult task for fresh crop SCs because of their inherent sources of uncertainty (e.g. yield quantities and dates) and the shelf-life that limits the storage of harvested quantities, increasing waste and unmet demand. Therefore, it is necessary to define strategies to manage and mitigate the risks associated with the crop price volatility (Sidhoum & Serra, 2016) and to reduce food losses and unmet demand that benefits farmers, consumers, and the environment (Suthar et al., 2019).

In view of all above, the present study is aimed at contributing to one of the future key objectives of the Common Agricultural Policy (CAP) (European Comission, 2020) related to the improvement of farmers' power position in the food value chain through the development of tools for mutually beneficial cooperation for a fair distribution of gains among them and sustainability. For doing so, we addressed the following research questions (RQs) that, in turn, constitute the contributions of this paper:

- RQ1: Which is the impact of different collaborative scenarios and widespread farmers' agricultural practices on SC sustainability (gross margin, waste, and unmet demand) on each farmer, the whole SC, and the unfairness among farmers?

- RQ2: Is it possible to define a collaborative approach in a real distributed scenario that allows obtaining nearly optimal solutions as compared to the centralized decision-making approach minimizing the unfairness among farmers?
- RQ3: Which optimization models can be developed in each scenario to support farmers for planting and harvesting of crops that mature over time (fresh tomato)?
- RQ4: How does the modelling of different uncertain sources impact on the solutions obtained and the answer to the above research questions?

To provide a response to the above RQs, a set of novel distributed and centralized mathematical programming models for the crop planning problem of fresh tomato SCs have been proposed in a deterministic and uncertain context by Fuzzy Sets under different scenarios. Through these scenarios, some of the most common agricultural practices as well as a novel collaboration scheme are defined, modelled, evaluated, and compared from the sustainability viewpoint for the planned and real situations.

The rest of the paper is structured as follows. The analysis of related research and the novelties of this study as regards existing literature on fresh tomato SCs are presented in detail in Section 2. The problem description is made in Section 3, while the different decision-making scenarios are presented in Section 4. The distributed and centralized mathematical programming models in deterministic and uncertain context for the cropping plan problem involving multiple farmers under different Scenarios are presented in Section 5. Section 6 presents the methodology adopted for solving the fuzzy models. In Section 7, the validation and result analysis of the proposed models for each Scenario is performed by their application to a case study of an Argentinian Tomato Supply Chain. Finally, in Section 8, conclusions and future research lines are outlined.

2. Related literature analysis and contributions of this study

This section first analyses the existing literature implementing different crop planning strategies (Section 2.1) based on which the corresponding Scenarios will be defined in Section 4. Then the mathematical programming models (MPMs) for planting and/or harvesting problems in fresh tomato SCs are revised (Section 2.2). Finally, the contribution of our paper as compared the existing literature is shown (Section 2.3).

2.1. Crop planning strategies in AFSCs

As commented before, in the face of unknown demand, farmers usually adopt as a strategy to produce more for the most profitable crop last season without any limitation in the planted area (e.g. Liu, Li, Huang, Zhuang, & Fu (2017)). Since each crop has different trends of price, yield (Lee, Bogner, Lee, & Koellner, 2016) and demand patterns, another common agricultural practice to reduce the risk of economic losses is by planting several crops. A very widespread way of implementing this diversification strategy consists of limiting the maximum and minimum areas to be planted for each crop (e.g. Chetty & Adewumi, 2014; Srivastava & Singh, 2017). Under the assumptions that all the planted area is going to be harvested and sold, farmers estimate their profits (planned or *a priori* evaluation). But when the final demand is known and the harvested quantities of the planted crops of all farmers are put together in the market, high quantities of waste and unmet demand exist that make the previously planned profits not to be real. Despite this, we have not found any research that assesses the impact of the above strategies when the real demand is known (real or *a posteriori evaluation*). This paper does so, being one contribution of this research.

Another strategy to reduce price volatility equilibrating supply and demand is to estimate the demand forecasts per region and to centrally decide about the planting and harvesting for all the farmers. Although this centralized approach provides with the

AFSC optimal solution, it could produce inequalities in the profits of farmers that compare them to those obtained by others creating a fairness concern (Moon, Jeong, & Saha, 2018). Despite this, it draws attention that we have only found one MPM in the agriculture sector that tries to find a fair solution for all farmers. For this, Li, Rodriguez, Zhang, & Ma (2015) introduce some constraints in their centralized model limiting the difference in profits obtained among farmers. In addition, implementing the centralized strategy is not always possible due to organizational, information and mistrust barriers (Stadtler, 2009), limiting its applicability.

This is the case of the primary sector that is fragmented with numerous small farmers acting independently (European Commission, 2017). Therefore, a more real alternative consists in adopting a distributed decision-making at the farmer stage and implementing collaboration mechanisms among them**.** Despite SC collaboration is a very established field in the literature (e.g. group buying), specific research for the agri-food sector is very scarce. Indeed, Plà, Sandars, & Higgins (2014) and Handayati et al. (2015), in their literature reviews, conclude that studies on SC coordination in the agri-food sector with a particular focus on small-scale farmers are in its early development. Moreover, research addressing coordination among actors in the same stage (horizontal) specifically at the farmer stage is even more limited (Plà et al., 2014). This paper addresses this type of collaboration.

Prima Dania et al. (2016) defines horizontal collaboration as the relationship among stakeholders that play at the same level including competitors and complementary, as well as external parties such as government, NGOs, associations, and universities. Horizontal collaboration can range from informal contracts between producers themselves to formal contracts facilitating joint actions through farmers' associations like cooperatives (Warsanga, 2014). In fact, SC contracts are one of the most popular coordination mechanism for AFSC from the theoretic and practical point of view (Zhou, Zhou, Qi, & Li, 2019). Zheng et al. (2017) identified in their review of SC contracting coordination for fresh products, that literature is very sparse and mostly focused on non-perishable products. Additionally, these contracts usually involve vertical integration among stakeholders of different stages. Up to our knowledge, there is only one paper in the literature (Mason & Villalobos, 2015) that proposes a decentralized mathematical model for the horizontal collaboration among farmers associated with agricultural cooperatives by means of defining appropriate contracts on prices and quantities harvested through an auction mechanism. However, the results obtained are not transferable to our case because it fits neither with cooperatives nor with contract signature. Instead, our problem assumes that farmers act independently to face the market demand, which is in concordance with the reality in several regions (e.g. Brittany, Argentine).

Another form of collaboration consists in information sharing (Simatupang & Sridharan, 2005). Mittal, White, & Krejci (2017) distinguish three different levels based on the amount of information exchanged between the collaborating organizations (operational, strategic, and co-evolution) being the operational level the one with the lower commitment, fewer interactions, and minimal information sharing among partners. Kembro & Näslund (2014) affirm that research on information sharing has mainly focused on dyadic relationships rather than on the entire SC. Sharing demand information to upstream SC members becomes an effective strategy to balance supply and demand in general (Cannella, Dominguez, Framinan, & Bruccoleri, 2018) maintaining the independence of each member and ensuring optimal decisions beneficial for the entire AFSC (Handayati et al., 2015) more specifically.

Horizontal collaboration for small farmers in AFSCs is different from other sectors because of their behavioural biases such as (European Commission, 2017): their independence having control of their own decisions; their individualism that leads farmers to see their fellow farmers as natural competitors may drive their reluctance to engage in formal forms of cooperation and the lack of trust, lack of social capital, along with lack of communication and mutual understanding between farmers have been shown to discourage farmers from engaging in collective actions.

In view of this situation, more research dealing with the decentralized nature of decision making in the AFSCs should be developed including collaboration mechanisms with minimal information sharing that encourage farmers to collaborate. In doing so, we should consider the specific characteristics of the agricultural sector: perishability, variable and uncertain yields and demand, volatile market prices, and the very long lead times from planting to harvest time that complicates the matching between supply and demand increasing waste and farmers' losses. The next section analyses these aspects for the fresh tomato AFSC in particular.

2.2. Planting and harvest MPMs in fresh tomato SCs

The existing specific MPMs for addressing the planting and/or harvesting problems in tomato SCs and generic MPMs applied to tomato SCs are analysed as regards the most relevant aspects of our proposal (Tables 1, 2, and 3) and compare with it (last row). The research gaps in planting MPMs covered by our research have been shaded. Fifteen papers dealing with the problem under study have been found. The first three papers (shaded in grey) although not consider planting decisions, consider harvesting ones that are also included in our models. In view of the literature analysis (Table 1), none of the revised planting MPMs has been specifically developed *ad hoc* for fresh tomato nor has addressed the specific characteristics of this crop. Instead, they have been formulated in a generic form and applied to several crops, including the fresh tomato.

Table 1. Characteristics of MPMs for planting and/or harvest planning of fresh tomato

	Crops		Spatial Level			Decision making approach		Objective function				Demand faced by Farmers		
Reference	Only tomato	Tomato & Others	Single Farmer	Multiple Farmer	Region	Centralized	Distributed	Max. Profits	Min. Costs	Min. Unfairness	Others	Market	Production Plants	Contracts
Miller, Leung, et al., (1997)	X			X		X			X				X	
Ahumada & Villalobos (2011b)		X	X	X		X		X				X		X
Suthar et al. (2019)	X		X	X		X		X				X		X
Mishra, Adhikary, & Panda (2009)		X			X	X		X			X			
Ahumada & Villalobos (2011a)		X	X	X		X		X						X
Ahumada, Villalobos, & Mason (2012)		X	X	X		X		X						
Tan & Çömden (2012)		X	X	X		X		X						X
Chetty & Adewumi (2013)		X	X			X		X						
Cid-Garcia et al. (2014)		X	X			X		X						X
Costa, dos Santos, Alem, & Santos (2014)		X	X			X						X		
Rachmawati, Ozlen, Hearne, & Kuleshov (2014)		X	X			X		X						
Otoo, Ofori, & Amoah (2015)		X	X			X		X						
Sinha, Singh, Ahmad, Chahal, & Meena (2018)		X			X	X		X						
Flores & Villalobos (2018)		X		X	X	X		X				X		
Flores et al. (2019)		X		X	X	X		X				X		
This paper	**X**			**X**		**X**	**X**	**X**		**X**		**X**		

Despite more than half of the papers contemplate the existence of multiple farmers, all of them assume centralized decision-making. This shows a lack of distributed models to support crop planning not only for AFSCs in general but also for fresh tomato SCs., All the centralized MPMs integrating several farmers aim at either maximizing profits or minimizing costs: none of them introduce any mechanism to ensure the optimal solution to benefit all SC members being a fair solution. So there is a need to develop new models to manage agri-food SCs while filling this gap. There are six planting models that do not take into account any demand information assuming that the whole yield of the planted area is harvested and consequently sold. Instead, all of them except Otoo et al. (2015) define minimum and/or maximum areas to be planted for each crop that coincides with the first two strategies described in Section 2.1.

As regards the considered decisions in the MPMs, none of the revised papers has considered the cultivating operations (Table 2), although they can compete for the scarce resources, due to their possible overlapping with planting and harvesting activities of different crops. Other less considered decisions are the unmet demand and waste. None planting model include the possibility of deciding on harvesting patterns characteristic for tomato crops that mature overtime. Surprisingly, although the limited shelf-life is one of the most relevant characteristic of fresh crops, only two planting models (Ahumada & Villalobos, 2011a; Costa et al., 2014) and one harvesting model (Ahumada & Villalobos, 2011b) have considered it.

As it can be seen in Table 3, four models include uncertainty: three of them, model uncertain parameters as stochastic (Ahumada et al., 2012; Costa et al., 2014; Tan & Çömden, 2012) and only one model them as fuzzy (Miller et al., 1997), but this last one not for planting decisions. Stochastic approaches imply that it is possible to estimate the probability distribution of random parameters (Esteso et al., 2018). Zeng, Kang, Li, Zhang, & Guo (2010) pointed out that for the cropping plan problem the estimation of proper distribution of uncertain parameters is not always possible due to difficulty in obtaining (i) historical data (Alemany, Grillo, Ortiz, & Fuertes-Miquel, 2015), and the estimation of variance and mean not being possible to apply stochastic programming. Arunkumar & Jothiprakash (2016) affirm that crop production becomes more uncertain because of the vagueness and impressions regarding the price of crops, crop yields, non-availability of land, and water resources. In a situation like this, Fuzzy

Sets Theory has proved their validity to manage uncertainty (Joolaie, Abedi Sarvestani, Taheri, Van Passel, & Azadi, 2017; Mundi, Alemany, Poler, & Fuertes-Miquel, 2016).

Table 2. Characteristics of MPMs for planting and/or harvest planning of fresh tomato

	Decisions												Problem Characteristics			
Reference	Planting	Cultivating	Harvesting	Packaging	Inventory	Transport	Labour	Waste	Unmet Demand	Backlog	Irrigation	Technology	Min/Max Area (agricultural policy)	Harvest Patterns	Yield dependent on harvest patterns	Product shelf-life
Miller et al. (1997)			X	X	X					X						
Ahumada & Villalobos (2011b)			X	X	X	X	X	X						X	X	X
Suthar et al. (2019)			X	X	X	X	X	X						X	X	
Mishra et al. (2009)	X										X		X			
Ahumada & Villalobos (2011a)	X		X	X	X	X	X						X			X
Ahumada et al. (2012)	X		X	X		X	X						X			
Tan & Çömden (2012)	X															
Chetty & Adewumi (2013)	X										X		X			
Cid-Garcia et al. (2014)	X										X					
Costa et al. (2014)	X		X		X			X	X							X
Rachmawati et al. (2014)	X		X										X			
Otoo et al. (2015)	X															
Sinha et al. (2018)	X										X		X			
Flores & Villalobos (2018)	X		X	X		X					X	X	X			
Flores et al. (2019)	X		X	X	X	X					X	X	X			
This paper	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**				**X**	**X**	**X**	**X**

As can be seen (Table 3), uncertainty has not been considered in parameters such as times for planting, cultivating and harvesting activities, and lower and upper limits of the planted area. Although costs such as unmet demand, backlogs, or waste are subjectively defined to penalize their inclusion in the optimal solution, the cost of unmet demand has been considered uncertain only by Miller et al., (1997) and backlog and waste cost has not been modelled under uncertainty.

Table 3. Uncertain modelling of MPMs for planting and/or harvest planning of fresh tomato supply chains

	Modelling context		Uncertain Modelling		Uncertain parameters																	
Reference	Deterministic	Uncertain	Stochastic	Fuzzy	Harvest capacity	Gassing capacity	Overtime limit	Time to plant	Time to apply phytosanitary products	Time to stake up plants	Time to prune plants	Time to harvest	Time to pack	Yield	Maturation period	Harvesting period	Min/Max area (Risk diversification)	Cost of waste	Cost of unmet demand	Backlog cost	Demand	Price
Miller et al. (1997)	X	X		X	X	X	X						X	X					X		X	
Ahumada & Villalobos (2011b)	X																					
Suthar et al. (2019)	X																					
Mishra et al. (2009)	X																					
Ahumada & Villalobos (2011a)	X																					
Ahumada et al. (2012)		X	X											X								X
Tan & Çömden (2012)		X	X											X	X	X					X	
Chetty & Adewumi (2013)	X																					
Cid-Garcia et al. (2014)	X																					
Costa et al. (2014)		X	X																		X	
Rachmawati et al. (2014)	X																					
Otoo et al. (2015)	X																					
Sinha et al. (2018)	X																					
Flores & Villalobos (2018)	X																					
Flores et al. (2019)	X																					
This paper		**X**		**X**				**X**	**X**	**X**	**X**	**X**	**X**	**X**			**X**	**X**	**X**		**X**	**X**

2.3. Identification of research gaps addressed in this study

In view of the literature analysis, this paper aims to improve the AFSC sustainability by covering the following gaps detected in the literature (in parenthesis their relationships with the corresponding RQs):

- There is a lack of distributed models for the crop planning problem that reflect the high fragmented decision-making at the farmer stage and define collaboration mechanisms aligned with the independence behavioural biases of small farmers. To cover this gap, we model the crop planning problem in a distributed and centralized manner under several scenarios considering different farmers' agricultural practices of the real world and modelled in the literature. Additionally, we propose a horizontal collaboration mechanism at the operational level based on minimal information sharing not among farmers but instead between each farmer and a third party (e.g. a governmental agency acting as a mediator) that respects the decision-making independence of farmers boosting their collaboration (RQ1&RQ2).
- There are aspects not previously modelled for the planting problem in fresh tomato SCs in isolated or jointly such as harvesting patterns, cultivating activities, consideration of imbalance between supply and demand, and their impact in terms of unmet demand and inventory that can become waste because of the shelf-life. This paper proposes novel deterministic mathematical programming models for each scenario to support the planting and harvesting decisions of fresh tomatoes in a multi-farmer context including these aspects (RQ3).
- Some parameters of the problem under study have not been modelled under uncertainty and no fuzzy planting model has been found for the fresh tomato SCs. In this paper, the above deterministic mathematical models are formulated,

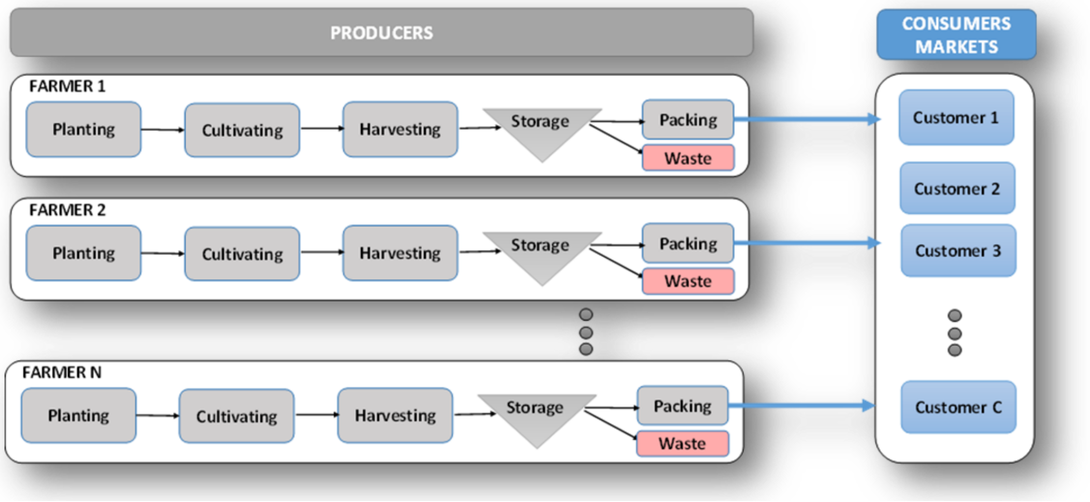
considering the uncertainty by fuzzy sets, in parameters previously not considered (times required to make cultivating activities, maximum and minimum planted areas per crop, yield depending on the harvesting patterns, unmet demand costs, waste costs, demand and price markets) (RQ4).

- No research has been found that compare the real performance measures per farmer and for the whole SC among the above strategies not only in the planned situation (*a priori* evaluation) but also in the real situation (*a posteriori evaluation*) when all the individual planting and harvesting decisions per farmer from the distributed models are integrated to satisfy SC market demands. In this paper, the planned and real performance is measured from a sustainable point of view taking into account not only the economic aspect (profits) but also other sector-specific aspects such as the environmental (waste) and social (unmet demand and unfairness among farmers) ones in deterministic and uncertain contexts (RQ1, RQ2, RQ3 & RQ4).

3. Problem description

The SC under study is integrated by several independent farmers that directly supply fresh tomato varieties to different markets without any intermediary (Figure 1), using mainly as a primary marketing channel the concentrator markets, supermarkets, hypermarkets, restaurants, greengrocers and final consumers. In the considered SC, farmers (producers) are responsible for almost all the activities of the chain: they not only plant, cultivate and harvest as usual but also pack and ship their product to the markets. These producers are often termed grower-shippers (Suthar et al. 2019). This is usual in some regions like Florida (The United States) or La Plata (Argentina). Indeed, the problem statement herein derives from real tomato SCs in Argentina studied in the framework of the European Project RUC-APS.

Figure 1. Fresh tomato supply chain



Each area of farmers' land can be planted during different weeks along the year but only once per season. The planting week determines the time interval for cultivating, during which several activities are carried out that require manual labour. These cultivating activities include some that are specific for land (e.g. fertilization) while others for tomato plants (e.g. stake, pruning, phytosanitary application). The planting week also determines the harvest periods. Because tomatoes mature over time, to harvest ripe tomatoes, plants require to be harvested all weeks along the harvesting periods. Based on the frequency of harvesting passes, several harvesting patterns exist (i.e, every day, every two days, once a week, etc) that can be applied in the same period in different land areas, and in the same land area in different periods. Manual labour required and yield obtained are dependent on the harvesting pattern: the higher the harvesting passes, the higher the yield and needs of manual labour and vice-versa.

The farmers' production of each tomato variety is destined to satisfy the demand in different markets that depends on the tomato variety and the period (seasonal demand). The selling price of tomato is assumed to be dependent on the variety, market, and period. Even though there is a relationship between the selling price and the ratio of demand and supply, it is assumed that the price is exogenous to our models. Instead, uncertainty is considered in both demand and selling price to reflect their volatility.

Although the vast majority of planting models do not include the perishability aspect, our model takes it into account by means of the shelf-life. The shelf-life limits the maximum number of periods the tomatoes can be stored once harvested. The tomatoes are packed just before being delivered to markets. Transport times are supposed to be less than one period reflecting local trade. It is assumed that all the tomato quantities transported to each market are to be sold, otherwise, they are not transported. This can cause part of the harvest to become waste if they are not consumed during their shelf-life. Unmet demand can also exist as a consequence of the shortage of supply in comparison with demand.

Since weeks exist that is possible to plant, cultivate and harvest several pieces of land simultaneously, different activities can overlap significantly in time, competing therefore for the limited capacity of laborers. To ensure a feasible planting, cultivating, harvesting, and packaging plan to satisfy market demand, the labour capacity consumed to perform such activities for all tomato varieties are considered as (Ahumada and Villalobos 2011b), but here additional cultivation activities in greenhouses are included. The necessary seasonal and temporary laborers per period and farmland are limited to a maximum and should be decided. Costs are incurred only for the hiring and firing of seasonal laborers since temporary laborers can be hired weekly as needs arise, but at a premium.

It is noteworthy that the crop planning problem is analogous to the classical Aggregate Planning Problem for which manpower capacity calculation constitutes a key aspect. Therefore, considering the time required for various operations allows us to include labour capacity constraints anticipating decisions on the hiring and firing of laborers and their associated costs. Due to the perishability, more operative aspects such as harvest times and quantities and the products' shelf-life have been also anticipated at this level in order to properly match supply and demand. The shelf-life consideration ensures that tomatoes reach markets with the appropriate freshness once harvested contributing, therefore, to the food security. Waste can be calculated and properly penalized in the objective function leading to its minimization and contributing to the environmental sustainability.

In short, the solution to our models support farmers as regards three main groups of decisions related to: 1) when and how much to plant, cultivate and harvest per tomato variety and harvesting mode, 2) when and how much to store, distribute and sell of each tomato variety in each market as well as the unmet demand and wasted quantity due to their limited shelf-life and 3) the size of labour resources required to perform the different activities per period. The definition of these decision variables allows us to take the three dimensions of sustainability into account in the objective function: economic (gross margin), environmental (post-harvest waste), and social (unmet demand). Besides including, wherever possible, waste and unmet demand penalizations in the objective function will contribute to balance supply and demand, reducing market price uncertainties. Additionally, the unfairness among farmers as another social aspect has been evaluated for different scenarios.

4. Description of Scenarios

Although in most cases farmers act individually, the literature of distributed decision-making models for the crop planning problem is very scarce (see Sections 1 and 2). This study intends to cover this gap. For doing so, several scenarios representing different widespread farmers' practices and levels of collaboration are defined and modelled by a set of distributed models to provide an answer to the RQ1 and RQ2. The organizational situation of fully centralized decision-making is also analysed and taken as a benchmark. Then, four scenarios have been defined with the following characteristics (Table 4) that require the formulation of different MPMs:

- **Distributed scenario (Scenario D)**. In this scenario, there is no collaboration among farmers. It is assumed a distributed decision-making situation where each farmer based on its own MPM independently decides when and how much to plant, harvest, package, store, and distribute to markets for each tomato variety. Farmers do not have any knowledge about neither the market demand, nor the other farmers' decisions. So, they implicitly consider that all quantities harvested will be completely sold assuming, therefore, the unmet demand be equal to zero.
- **Distributed scenario with limited land areas (Scenario DAm)**. This scenario is mainly the same as Scenario D, but in an attempt to diversify their investment and reduce risk in the absence of market demand knowledge, farmers limit the minimum and maximum area allocated to each crop along the horizon in a proportional way to the crop expected gross margin. This scenario attempts to model the usual practice of farmers of increasing production for the more profitable crops last season. In the same way as in scenario D, it is assumed that unmet demand will be null.
- **Distributed scenario with information sharing (Scenario DIS)**: It corresponds with the horizontal collaboration mechanism through a third party (governmental entity) based on minimal information sharing. In this scenario, cropping plan decisions are also made in a distributed manner by each farmer with as many models as farmers exist. However, unlike the Scenario DAm, farmers have been provided with information about the market demand forecasts

for each tomato variety according to their areas. This implicitly assumes that there is some mediator (e.g. government agency) that knows not only on the market demand forecasts for each crop but also on the area of every farmer. This agency provides this minimal information to each farmer orchestrating the horizontal collaboration among farmers in order to contribute to a more balanced situation between supply and demand. It is important to note that this scheme differs from typical contract farming, because it respects the independence of farmers for making their own decisions. Indeed, once farmers receive the information on the demand from the mediator, each farmer individually decides the quantity of this demand to be served, and therefore, the unmet demand quantities and also their associated penalty (cost).

- **Centralized scenario (Scenario C)**: In this situation, decisions for all farmers are made in a centralized way with only one MPM representing the highest level of collaboration (joint decisions). This scenario assumes that a single decision-maker exists with full knowledge of all farmers as well as the market demand forecasts for each tomato variety. Unlike the Scenario DIS, unmet demand is calculated for the SC and not per farmer since the supply of all farmers is used to serve the market demand in global terms. For this reason, the unmet demand and its associated cost is defined for the whole SC not differentiating among farmers.

Table 4. Characterization of scenarios for the cropping plan problem

Scenario	Collaboration		Decision making		Nº of MPMs (Decision-Makers)		Information on market demand		Unmet Demand	Min/Max land areas limits (Minimize risk)	
	No	Yes	Dist	Cent	NF	One	No	Yes	Value	No	Yes
D	X		X		X		X		Zero	X	
DAm	X		X		X		X		Zero		% crop margin

DIS	Information sharing	X		X		X	Non-negative	X
C	Joint decisions		X		X	X	Non-negative	X

Dis: Distributed, Cen: Centralized; NF: No. farmers

At this point, it is important to note that Scenario D and DAm do not have any information on market demand. Therefore, both scenarios assume that all quantities harvested will be completely sold that is a typical assumption made by farmers in real-life and implemented in several MPMs found in the literature review. As a consequence of this assumption, the unmet demand will be equal to zero. For the first two scenarios this has two important implications from the mathematical modelling viewpoint: a) the decision variable of unmet demand does not need to be defined because it is *a priori* set to zero and, consequently, b) no penalization for the unmet demand needs to be included in the objective function. On the contrary, Scenario DIS and C consider the market demand allowing some demand not to be served (i.e the unmet demand can take a non-negative value) with its associated cost that can be different for each farmer (Scenario DIS) or defined for the whole SC (Scenario C), as explained just above.

5. MPMs for the cropping plan problem involving multiple farmers in different scenarios

Next subsections present the mathematical formulation and the description of the MPMs representing each Scenario.

5.1. MPM for each farmer in distributed Scenario D

In this scenario, each farmer makes their cropping plan decisions in a distributed manner based on the following MILP model without any type of collaboration. Therefore, the number of MILP models coincides with the number of farmers. All the information available for each farmer appears in Table 5. Uncertain parameters modelled by fuzzy sets are identified by the symbol (~). The deterministic model will be obtained from the fuzzy one by removing (~) from the corresponding uncertain parameters. It is worth mentioning that decision variables for the distributed scenarios finalize in "F" in order to highlight that the model is used individually by each farmer.

Table 5. Nomenclature for the Distributed MPM for Scenario D

Indices			
v	Tomato variety	w	Harvesting patterns
p	Planting period	t	Time period in general
h	Harvest period	m	Market
Set of indices			
P_v	Set of planting dates p in which tomatoes of variety v can be planted.		
H_v^p	Set of harvest dates h that correspond to each planting date p and tomato variety v		
PS_v^t	Set of planting dates p for tomato variety v that requires stake up activities at t		
PC_v^t	Set of planting dates p for tomato variety v that requires pruning activities at t		
PK_v^t	Set of planting dates p for tomato variety v that requires phytosanitary application at t		
PH_v^h	Set of planting dates p for tomato variety v that enables harvest at h		
Parameters			
aF	Total available area for planting tomatoes at farmer (ha)		
d_v	Density of cultivation of variety of tomato v (plants/ha)		
$amin_v$	Minimum area to be planted per period and variety, in case the variety is decided to be planted in that period (ha). This is due to technical reasons (not to minimize risk) and its value is known with certainty.		
$\tilde{y}_{vw}^{ph}$	Quantity of tomatoes obtained from a plant of variety v if planted at period p and harvested at period h following the pattern w (kg/plant)		
$\widetilde{tp}_v$	Time needed to plant one tomato plant of variety v (min/plant)		
$\widetilde{ts}_v$	Time needed per period to stake up one tomato plant of variety v (min/plant)		
$\widetilde{tc}_v$	Time needed per period to prune one tomato plant of variety v (min/plant)		
$\widetilde{tk}_v$	Time needed per period to apply phytosanitary products in one plant of variety v (min/plant)		
$\widetilde{th}_{vw}$	Time needed to harvest a tomato plant of variety v under pattern w (min/plant)		
$\widetilde{tpa}_v$	Time needed to pack one kilogram of tomato of variety v (min/kg)		
sl_v^{ph}	Shelf-life of tomato variety v if planted at period p and harvested in period h (week)		
hw	Available capacity per worker in a week (min/week)		
$MinLS$	Minimum number of seasonal workers per week		
$MaxLS$	Maximum number of seasonal workers per week		
$MaxLT$	Maximum number of temporary workers per week		
$\tilde{p}_{vm}^t$	Selling price for each tomato variety v at market m and period t (€/kg)		
cf_v	Cost incurred for planting and cultivating one tomato plant (€/plant).		
$\widetilde{cwa}_v$	Penalty unitary cost for wasting tomato of variety v after harvest (€/kg)		
ch_v	Holding cost of one kilogram of tomato of variety v per period (€/kg·week)		
ctF_{vm}	Cost of packing and transporting one kilogram of tomato of variety v from farmer to market m (€/kg)		
chs	Fixed cost of hiring one seasonal worker (€)		
cls	Cost per week for one seasonal worker (€/week)		
clt	Cost per week for one temporary worker (€/week)		
Decision variables			
NPF_v^p	Number of plants of tomato variety v planted at period p by the farmer (plant)		
YPF_v^p	Binary variable with a value of one if tomato variety v is planted by the farmer at planting date p and with a value of zero otherwise.		
NSF_v^t	Number of plants of tomato variety v to be staked and strung up at period t (plant)		

NCF_v^t	Number of plants of tomato variety v to be pruned at period t (plant)
NKF_v^t	Number of plants of tomato variety v that require the application of phytosanitary products at period t (plant)
$NHWF_{vw}^{ph}$	Number of plants of tomato variety v planted in period p harvested in period h by pattern w (plant)
QHF_v^{ph}	Quantity of tomatoes of variety v harvested at period h from plants planted at p (kg)
$WAHF_v^{ph}$	Quantity of wasted tomato variety v planted at period p and harvest at period h (kg). This waste is originated by the harvested tomatoes perishing before transported to markets.
QPF_v^{pht}	Quantity of tomato of variety v planted at planting period p, harvested at period h and packed at period t (kg). Product is packaged after storage just for being transported to markets, for this reason, the harvesting period could be different from the period when is packaged.
QTF_{vm}^{pht}	Quantity of tomato variety v planted at period p, harvested at period h and transported from farmer to market m at period t (kg). It represents the supply in the demand-supply balance.
LSF^t	Number of seasonal laborers working at week t
$HLSF^t$	Number of seasonal laborers hired at week t
$FLSF^t$	Number of seasonal laborers fired at week t
LTF^t	Number of temporary laborers working at week t
PrF	Profit obtained by the farmer (€)

This model aims at optimizing the gross margin obtained by each farmer individually as a difference between the incomes per sales and the total costs (1). As the farmer does not have information about the demand of tomatoes, for calculating the incomes per sales he/she assumes that all tomatoes transported to markets are going to be sold being the unmet demand equal to zero. Therefore, it is necessary neither to define any decision variable for the unmet demand nor to assign it any penalization in the objective function. On the other hand, to calculate the income per sales, the selling price will be multiplied by the transported quantities because of they are assumed to be equal to the sold quantities. The total costs include costs for planting and cultivating, holding costs, waste costs, transport costs, costs for hiring seasonal workers, and costs for seasonal and temporary labour. The shelf-life influences the objective function through two terms: the holding costs and the waste costs. The unitary holding costs are affected by the technology used to store fresh crops: for instance, refrigerated, special packages, etc. In turn, the technology used greatly impacts on the shelf-life. For instance, the refrigerated storage extends the shelf-life at the expense of increasing the unitary inventory holding costs due to energy consumption. On the other hand, the total inventory holding costs are assumed to be proportional to the number of periods crops are stored that cannot be higher than the shelf-life ($h \leq t \leq h + sl_v^{ph}$) otherwise, it becomes waste (see Eq. 11). Waste is associated with a penalty cost higher than its corresponding holding cost, to avoid it in the solution obtained. So, the higher the shelf-life, the higher the opportunity to store products for matching supply and demand, increasing the quantity sold, and decreasing waste.

$$Max[PrF] = \sum_v \sum_m \sum_{p \in P_v} \sum_{h \in H_v^p} \sum_t \tilde{p}_{vm}^t \cdot QTF_{vm}^{pht} - \sum_v \sum_{p \in P_v} cf_v \cdot NPF_v^p - \sum_v \sum_m \sum_{p \in P_v} \sum_{h \in H_v^p} \sum_t ch_v \cdot (t-h) \cdot QTF_{vm}^{pht} - \sum_v \sum_{p \in P_v} \sum_{h \in H_v^p} \widetilde{cwa}_v \cdot WAHF_v^{ph} - \sum_v \sum_m \sum_{p \in P_v} \sum_{h \in H_v^p} \sum_t ctF_{vm} \cdot QTF_{vm}^{pht} - \sum_t (chs \cdot HLSF^t + cls \cdot LSF^t + clt \cdot LTF^t) \tag{1}$$

$$\sum_v \sum_{p \in P_v} \frac{NPF_v^p}{d_v} \leq aF \tag{2}$$

$$\frac{NPF_v^p}{d_v} \geq amin_v \cdot YPF_v^p \qquad \forall v, p \in P_v \tag{3}$$

$$\frac{NPF_v^p}{d_v} \leq aF \cdot YPF_v^p \qquad \forall v, p \in P_v \tag{4}$$

$$NSF_v^t = \sum_{p \in PS_v^t} NPF_v^p \qquad \forall v, t \tag{5}$$

$$NCF_v^t = \sum_{p \in PC_v^t} NPF_v^p \qquad \forall v, t \tag{6}$$

$$NKF_v^t = \sum_{p \in PK_v^t} NPF_v^p \qquad \forall v, t \tag{7}$$

$$\sum_w NHWF_{vw}^{ph} = NPF_v^p \qquad \forall v, h, p \in PH_v^h \tag{8}$$

$$\sum_w \tilde{y}_{vw}^{ph} \cdot NHWF_{vw}^{ph} = QHF_v^{ph} \quad \forall v, p \in P_v, h \in H_v^p \tag{9}$$

$$QHF_v^{ph} = \sum_m \sum_{h \leq t \leq h + sl_v^{ph}} QTF_{vm}^{pht} + WAHF_v^{ph} \qquad \forall v, p \in P_v, h \in H_v^p \tag{10}$$

$$QPF_v^{pht} = \sum_m QTF_{vm}^{pht} \qquad \forall v, p \in P_v, h \in H_v^p, t \geq h \tag{11}$$

$$\sum_v \sum_{p=t} \widetilde{tp}_v \cdot NPF_v^p + \sum_v \widetilde{ts}_v \cdot NSF_v^t + \sum_v \widetilde{tc}_v \cdot NCF_v^t + \sum_v \widetilde{tk}_v \cdot NKF_v^t + \sum_v \sum_{p \in P_v} \sum_w \sum_{h=t} \widetilde{th}_{vw} \cdot NHWF_{vw}^{ph} + \sum_v \sum_{p \in P_v} \sum_{h \in H_v^p} \widetilde{tpa}_v \cdot QPF_v^{pht} \leq hw \cdot (LS^t + LT^t) \quad \forall t \tag{12}$$

$$LSF^t = LSF^{t-1} + HLSF^t - FLSF^t \qquad \forall t \tag{13}$$

$$MinLS \leq LSF^t \leq MaxLS \qquad \forall t \tag{14}$$

$$LTF^t \leq MaxLT \qquad \forall t \tag{15}$$

$$\begin{array}{ll} PrF, QPF_v^{pht}, QHF_v^{ph}, WAHF_v^{ph}, QTF_{vm}^{pht} & CONTINUOUS \\ NPF_v^p, NSF_v^t, NCF_v^t, NKF_v^t, NHWF_{vw}^{ph}, HLSF^t, LSF^t, FLSF^t, LTF^t & INTEGER \\ YPF_v^p & BINARY \end{array} \tag{16}$$

Since available land area at farms can only be planted once per season, set of constraints (2) ensure the total area planted with the different tomato varieties plants along all the planting periods is not higher than the available farmer area to be planted.

Set of constraints (3) fixes the minimum area each time a specific variety of tomatoes is planted due to technical reasons and not to minimize the risk. Set of constraints (4) forces the binary variable YPF_v^p to be 1 if the tomato variety v has been planted during period p, ensuring that the minimum area to be planted is respected by constraint (3). These two sets of constraints also act oppositely, i.e. if a specific variety is not planted, constraint (3) obliges YPF_v^p to be zero.

The number of plants to be staked up in each period t depends on the number of plants planted at planting periods p that require this operation to be done at t (5). Analogously to constraints (5), constraints (6) and (7) calculate the number of plants to be pruned and to applicate phytosanitary products in each period, respectively.

Set of constraints (8) ensure that the total number of plants per tomato variety v harvested during period h with the different harvesting patterns w is equal to the total number of plants planted during period p where harvesting at h is possible. This constraint assumes that all the plants planted at period p that can be harvested at period h, are harvested. It is important to note that the same plant planted at period p can be harvested during different periods h because tomatoes mature over time.

The amount of each tomato variety v planted at p and harvested during period h is equal to the sum of the amount of the same tomato variety harvested by the different patterns (9).

By means of constraint (10), it is ensured that the quantity of tomato variety v planted at p and harvested h will be equal to the quantity of tomatoes transported and sold at all markets during their corresponding shelf-life plus the waste originated by product that perishes. The freshness of the product delivered at the market will be equal to $(t-h)/sl_v^{ph}$. Constraint (11) assumes that transported quantities in a specific period are packaged in the same period t. This means that the tomatoes cannot be stored when packaged.

The time used to do the planting, cultivating (staking, pruning, application of phytosanitary products), harvesting, and packing activities for all the planted areas per period cannot exceed the defined available capacity of seasonal and temporary workers for the period (12). The set of equations (13) allows calculating the number of seasonal workers hired and fired at each period. A minimum and a maximum number of seasonal workers exist for all periods on the farm (14). Similarly, the available temporary workers are limited (15). The set of constraints (16) defines the nature of the decision variables of the model.

5.2. MPM for each Farmer with Limited Land Areas per Variety in Distributed Scenario DAm

This scenario is similar to the previous one with the difference that each farmer tries to minimize risk by means a diversification strategy in the tomato varieties planted. For doing so, limits about the minimum and maximum land area to be planted per tomato variety along the year are specified by each farmer. To model this, new parameters (Table 6) and a new constraint (17) should be included in order to accomplish with these limits.

Table 6. New parameters to the distributed model with limited land areas per variety (DAm).

Parameters	
$\widetilde{am}_v$	Minimum area to be planted per variety v during the horizon at farmer (ha)
$\widetilde{aM}_v$	Maximum area to be planted per variety v during the horizon at farmer (ha)

$$Max\ Z = PrF \tag{1}$$

Subject to:

Constraints (2) to (16)

$$\widetilde{am}_v \leq \sum_{p \in P_v} \frac{NPF_v^p}{d_v} \leq \widetilde{aM}_v \qquad \forall v \tag{17}$$

5.3. MPM for each Farmer with Shared Information about Market Demands for the Distributed Scenario DIS.

The Scenario DIS involves the existence of some organisms like public agencies acting as a mediator and providing farmers with information about the market demand for each tomato variety. The demand per period and tomato variety for each farmer ($\widetilde{deF}_{vm}^{t}$) is calculated by proportionally distributing the total market demand for this variety and period ($\widetilde{de}_{vm}^{t}$) among farmers to the specific farmer area (aF) as regards the total available area of all farmers (ta) (18).

$$\widetilde{deF}_{vm}^{t} = \frac{\widetilde{de}_{vm}^{t} \cdot aF}{ta} \qquad \forall v, m, t \tag{18}$$

In this scenario, each farmer decides independently how to serve the demand provided by the mediator ($\widetilde{deF}_{vm}^{t}$) by means defining the planted and harvested tomato quantities of each variety and time period. In this situation, it is possible to appear waste of a variety when its demand is lower than its supply during their shelf-life. Meanwhile, unmet demand will appear when supply is lower than the market demand. For this reason, two new decision variables for unmet demand (UD_{vm}^{t}) and quantity sold (QSF_{vm}^{pht}) should be defined as well as their associated penalties in term of costs (Table 7). It is noteworthy that in Scenario DIS each farmer is autonomous to decide the costs associated to the expired excess (waste) and the shortage (unmet demand) in supply, being possible that different farmers use different costs depending on their preferences. The new model appears below.

Table 7. New parameters and decision variables to the Distributed Model with Shared Information about Market Demand per farmer (DIS).

Parameters	
$\widetilde{deF}_{vm}^{t}$	Proportional demand of farmer for the tomato variety v at market m and period t (kg)
$\widetilde{cud}_{vm}$	Penalty unitary cost for not fulfilling tomato of variety v at market m (€/kg)
Decision variables	
UD_{vm}^{t}	Quantity of unmet demand of tomato variety v at period t in market m (kg)
QSF_{vm}^{pht}	Quantity of tomatoes of variety v planted at p, harvested at h and sold at period t in market m (kg)

Because penalties for unmet demand exists, the objective function of this scenario should be modified to consider them (19). Through these penalties, a more sustainable solution is achieved because not only the economic results are taken into account but also the environmental (waste) and social (unmet demand) ones.

$$
\begin{aligned}
Max\ PrF = {} & \sum_{v}\sum_{m}\sum_{p\in P_v}\sum_{h\in H_v^p}\sum_{t}\tilde{p}_{vm}^{t}\cdot QSF_{vm}^{pht} - \sum_{v}\sum_{p\in P_v} cf_v \cdot NPF_v^p \\
& -\sum_{v}\sum_{m}\sum_{p\in P_v}\sum_{h\in H_v^p}\sum_{t} ctF_{vm}\cdot QTF_{vm}^{pht} \\
& -\sum_{v}\sum_{m}\sum_{p\in P_v}\sum_{h\in H_v^p}\sum_{t} ch_v\cdot (t-h)\cdot QTF_{vm}^{pht} \\
& -\sum_{v}\sum_{p\in P_v}\sum_{h\in H_v^p} \widetilde{cwa}_v \cdot WAHF_v^{ph} - \sum_{v}\sum_{m}\sum_{t}\widetilde{cud}_{vm}\cdot UD_{vm}^{t} \\
& -\sum_{t}(chs\cdot HLSF^t + cls\cdot LSF^t + clt\cdot LTF^t)
\end{aligned} \tag{19}
$$

Subject to:

$Constraints\ (2)-(16)$

$$QTF_{vm}^{pht} = QSF_{vm}^{pht} \qquad \forall v,m,p\in P_v, h\in H_v^p, t \tag{20}$$

$$\sum_{p\in P_v}\sum_{h\in H_v^p} QSF_{vm}^{pht} + UD_{vm}^{t} = \widetilde{deF}_{vm}^{t} \qquad \forall v,m,t \tag{21}$$

$$QSF_{vm}^{pht}, UD_{vm}^{t} \qquad CONTINUOUS \tag{22}$$

Because neither stock nor waste are allowed at markets, constraint (20) assumes all the tomatoes quantities transported to each market to be sold, otherwise, they are not transported. Therefore, the total quantity sold per tomato variety and period in each market should be equal to the demand allocated to this farmer for the same variety and period minus the unmet demand (21). Finally, the nature definition of the new decision variables is stated in (22).

5.4. MPM for all farmers in Centralized Scenario C

This scenario assumes the existence of one decision-maker with knowledge on the market demand forecasts and information of all farmers including their available land area. The decisions are made to optimize the farmers' profit as a whole, that is, at the region or SC level. For this reason, the global demand for each market should be satisfied considering the production of all farmers. In order to identify decisions related to each farmer, a new index f for farmers has been defined. This index is included in all parameters and decision variables of one farmer in particular.

The difference between the objective function of this centralized scenario and the previous distributed ones is that the profits and the costs include those of all farmers (note that different objective function terms are summed through the farmers' index *f*). In the same way as the model for Scenario DIS, this model contemplates demand and therefore, the three aspects of sustainability by considering not only the profit (economic) but also the penalties of waste (environmental) and unmet demand (social). But unlike the Scenario DIS that considers in each farmer MPM only the demand proportional to his/her land area ($\widetilde{deF}_{vm}^{t}$), the Scenario C includes the overall market demand to be covered by all farmers ($\widetilde{de}_{vm}^{t}$). As a consequence, the unmet demand and its associated cost are not established per farmer but for the entire Supply Chain. The MPM for the Scenario C as well as its detailed description can be consulted in Appendix A.

6. Solution Methodology for the Fuzzy Models

The models proposed to support the crop planning problem in different scenarios consider as another novelty the following uncertain parameters to be fuzzy due to either lack of knowledge ($\tilde{p}_{vm}^{t}$, $\widetilde{de}_{vm}^{t}$,$\widetilde{deF}_{vm}^{t}$, $\tilde{y}_{vw}^{ph}$, $\widetilde{tp}_{v}$, $\widetilde{ts}_{v}$, $\widetilde{tc}_{v}$, $\widetilde{tk}_{v}$, $\widetilde{th}_{vw}$, $\widetilde{tpa}_{v}$), vagueness or imprecision ($\widetilde{am}_{v}$, $\widetilde{aM}_{v}$, $\widetilde{cud}_{vm}$, $\widetilde{cwa}_{v}$). These parameters gather the uncertainty sources in demand and process by means of fuzzy numbers in the objective function coefficients (OC) and constraints for both, technological coefficients (TC) and right-hand side (RHS) (Table 8).

Table 8. Fuzzy parameters considered in the MPMs of different Scenarios

Sources of uncertainty	Fuzzy parameters	Model element	Formula-tion
Demand	Selling price for each tomato variety *v* at market *m* and period *t*	OC	$\tilde{p}_{vm}^{t}$

	Farmer proportional demand for tomato variety *v* at market *m* and period *t*	RHS	$\widetilde{deF}_{vm}^{t}$
	Demand of the tomato variety *v* at market *m* and period *t*	RHS	$\widetilde{de}_{vm}^{t}$
	Penalty unitary cost for not fulfilling tomato of variety *v* at market *m*	OC	$\widetilde{cud}_{vm}^{t}$
Process	Quantity of tomatoes from a plant of variety *v* if planted at period *d* and harvested at period *h* following the pattern *w* (yield)	TC	$\tilde{y}_{vw}^{ph}$
	Time needed to plant one tomato plant of variety *v*	TC	$\widetilde{tp}_{v}$
	Time needed per period to stake up one tomato plant of variety *v*	TC	$\tilde{y}_{vw}^{ph}$
	Time needed per period to prune one tomato plant of variety *v*	TC	$\tilde{y}_{vw}^{ph}$
	Time needed per period to apply phytosanitary products on one tomato plant of variety *v*	TC	$\tilde{y}_{vw}^{ph}$
	Time needed to harvest tomato plant of variety *v* with pattern *w*	TC	$\tilde{y}_{vw}^{ph}$
	Time needed to pack one kilogram of tomato of variety *v*	TC	$\tilde{y}_{vw}^{ph}$
	Minimum area to be planted per variety *v* during the horizon	RHS	$\tilde{y}_{vw}^{ph}$
	Maximum area to be planted per variety *v* during the horizon	RHS	$\tilde{y}_{vw}^{ph}$
	Penalty unitary cost for wasting tomato of variety *v* after harvest	OC	$\tilde{y}_{vw}^{ph}$

All the above models have been solved in a deterministic and uncertain context in order to assess the impact of modelling uncertainty on the different performance indicators, answering in this way to the RQ4. In the context of possibility theory, several methods exist to solve models involving coefficients of the objective function and/or the constraints as fuzzy numbers. In this paper, we followed a two-step methodology: First, we apply the approach of Jiménez, Arenas, Bilbao, & Rodríguez, (2007) to transform the fuzzy mixed-integer linear programming models into an equivalent α-parametric crisp models. In doing so, we adopt triangular fuzzy numbers (TFN) (symmetric and asymmetric) to model the epistemic uncertainty in all the fuzzy parameters. Mula, Peidro, & Poler (2010) state that the parameters of a triangular possibility distribution represent the most pessimistic, the most possible, and the most optimistic values, which is in concordance with our case. The resulting equivalent α-parametric crisp models for the fuzzy models of each scenario are in Appendix B.

Several solutions are obtained with the above α-parametric crisp models (as many as used α-value used). This makes necessary to select one α-value solution to be finally implemented. For that, we follow the three-stage interactive resolution method proposed by Peidro, Mula, Jiménez, & Botella (2010) to select the final solution according to the three dimensions of sustainability (economic, environmental and social). The first stage consists in solving the auxiliary crisp mixed-integer linear programming models proposed in Appendix B for each scenario and for 11 values of α (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0). Each farmer's solution is evaluated according to the following measurable parameters that are related to the three dimensions of sustainability:

- **Margin per Hectare:** it is calculated as the incomes per sales minus all the costs, except the penalties of unmet demand and waste ($Margin_f = PrF_f + Waste\ Penalty_f + Unmet\ Demand\ Penalty_f$) , divided by the farm area (a_f).

$$Margin\ per\ ha_f = \frac{Margin_f}{a_f} \tag{23}$$

- **% Waste:** it is calculated as the percentage of the quantity of waste as regards the whole quantity harvested.

$$\%\,Waste_f = 100 \cdot \left(\frac{Total\ Waste_f}{Total\ Quantity\ Harvested_f}\right) \tag{24}$$

- **%Unmet Demand:** it is calculated as the percentage of the unmet demand of all tomato varieties as regards the global demand.

$$\%\,Unmet\ demand_f = 100 \cdot \left(\frac{Total\ Unmet\ Demand_f}{Total\ Demand_f}\right) \tag{25}$$

For the centralized Scenario C, the above parameters should be calculated for the whole SC.

The second and third stage of the methodology intends to obtain a decision vector that complies with the expectation of the decision-maker as regards two conflicting aspects: the feasibility degree α and a satisfactory value for the three evaluation parameters by means of the calculation for each α of a joint acceptation index K_α and selecting the α-value with the highest K_α. For more details of this interactive resolution method, readers are referred to Peidro et al. (2010).

7. Computational Experiments: Application to an Argentine Fresh Tomato Supply Chain

The computational experiments designed in this section intend to: 1) validate the novel models proposed for each scenario in a deterministic and uncertain context, 2) analyse their solutions for the whole supply chain and for each farmer in order to assess the impact of different widespread farmers' agricultural practices and collaboration scenarios on different evaluation parameters, 3) compare the behaviour of the proposed fuzzy models with their deterministic versions and 4) obtain for each distributed scenario, the discrepancies between the planned results (solution of MPMs of each scenario) versus the real ones in which all the farmers' decisions are integrated and the market demands are considered.

Data from a realistic tomato supply chain integrated by ten farmers located in four different regions of La Plata (Buenos Aires) and two markets (Central Market of Buenos Aires and Restaurants) is considered. Farmers should decide on the allocation of their greenhouses area to three varieties of tomato: round, pear, and cherry. We assume that the planning horizon comprises a whole planting season of one year divided into 52 weeks. For a detailed description of the input data used, see Appendix C.

7.1. Experimental Design and Results

The experimental design (Figure 2) aims to provide an answer to the stated research questions (**RQ**) in Section 1. During the experimental methodology, the solutions obtained per farmer in different distributed scenarios under deterministic and uncertain contexts are used to obtain the planned and real evaluation of the whole SC as regards the following evaluation parameters: SC objective function, margin per ha, %waste, %unmet demand, and SC unfairness. The MPM for each farmer is solved under deterministic environment for each Distributed Scenario, (Figure 2). To calculate the above evaluation parameters for the whole SC, an aggregation along farmers is made as described below:

- *SC Objective Function* is calculated as the sum of the objective functions of all the SC farmers:

$$SC\ Pr = \sum_{f} Pr_f \tag{26}$$

- *SC Margin per ha* is calculated as the sum of the gross margin obtained by all SC farmers divided by the sum of all farmers' area (total SC area).

$$SC\ Margin\ per\ ha = \frac{\sum_f Margin_f}{\sum_f a_f} \tag{27}$$

- *SC % Waste* is computed as the percentage of the sum of the expired tomato quantities of all farmers as regards the harvested tomatoes by all farmers.

$$SC\ \%\ Waste = 100 \cdot \frac{\sum_f Waste_f}{\sum_f Harvest_f} \tag{28}$$

- *SC % Unmet Demand* is computed as the percentage of the sum of the unmet demand of all farmers as regards the SC total demand.

$$SC\ \%\ Unmet\ Demand = 100 \cdot \frac{\sum_f Unmet\ Demand_f}{SC\ total\ demand} \tag{29}$$

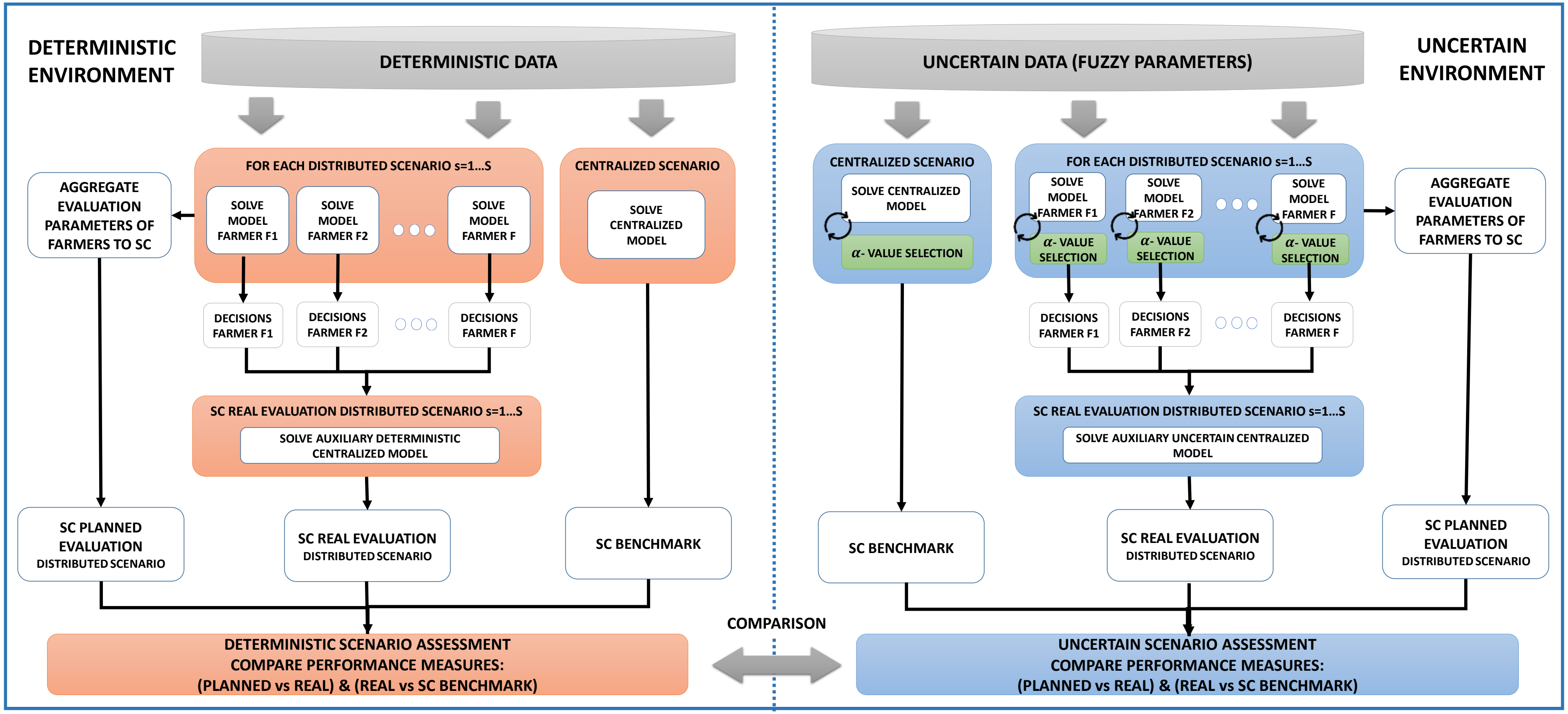
- *SC unfairness* is an evaluation parameter that tries to assess the disequilibrium in the obtained margin per hectare among farmers. Consequently, unfairness can only be computed when all farmers' solutions are known. Analogously to (Stadtler, 2009), we assume that unfairness results if one member faces an absolute deviation of margin per ha as regards the margin per ha for the SC. The SC unfairness for each scenario is determined by the percentage of the farmers' absolute deviation of margin per ha average as regards the SC margin per ha.

$$SC\ Unfairness = 100 \cdot \left(\frac{1}{nº\ farmers}\right)\sum_{f}\left(\frac{\left|Margin\ per\ ha_f - SC\ Margin\ per\ ha\right|}{SC\ Margin\ per\ ha}\right) \quad (30)$$

where:

$$SC\ Margin\ per\ ha = \frac{\sum_f Margin_f}{\sum_f a_f} \quad (31)$$

Figure 2. Experimental procedure designed to validate, assess, and compare Scenarios in a Deterministic and Uncertain Environment.



The obtained results are named ***SC Planned Evaluation*** for **Distributed Scenarios**. For **Scenario C**, SC results extracted from solving the MPM, are directly analysed, being the unfairness the only evaluation parameter that requires to be calculated for the whole SC. Because the centralized scenario provides the optimal solution for the SC objective function, it is considered as the ***SC Benchmark***.

However, the ***SC Planned Evaluation*** for Distributed Scenarios could not coincide with the real one when all the planting and harvesting decisions independently made by farmers are put together in the market to satisfy the market demands. We have named this ***SC Real Evaluation***. To calculate the ***SC Real Evaluation***, decisions made by all farmers in each distributed scenario are passed to an **Auxiliary Deterministic Centralized Model** in order to determine the impact of integrating such independent decisions of each farmer in a real situation where market demands are known. To formulate this auxiliary model, the demand assigned to each farmer has been proportional to his/her land area as in the Scenario DIS. Decisions related to the planting, cultivating, harvest of products, and labour are given to the auxiliary centralized model as input data. Since tomatoes cannot be wasted at markets, the transport decision remains as a decision variable in the auxiliary centralized model that should decide it based on market demands. Due to the relationship between the transport variable (QT) and quantity packed (QP), waste (WAH), quantity sold (QS), and unmet demand (UD), all of them remain as decision variables in the auxiliary centralized evaluation model. Through the solution of this model, the ***SC Real Evaluation*** parameters are calculated. The ***SC Planned Evaluation*** is compared with the ***SC Real Evaluation***, and the ***SC Real Evaluation*** against the ***SC Benchmark*** (Centralized Scenario C).

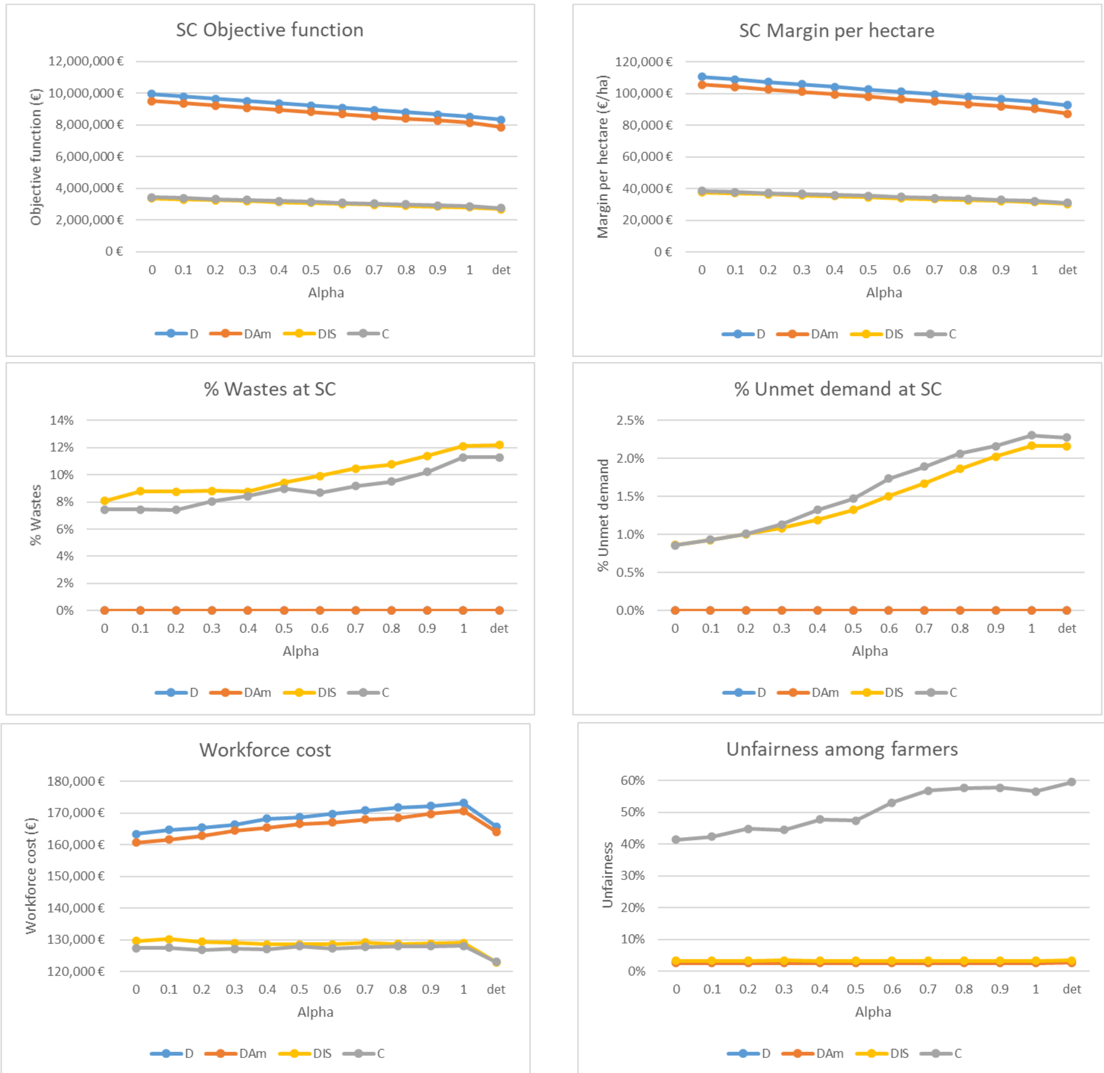
The evaluation process for the uncertain context is analogous to the deterministic one, except that it is necessary to apply the methodology of Peidro et al. (2010) to select the α-value for each farmer in order to obtain the final solution as an input to obtained the ***SC planned evaluation***. This implies to solve each MPM for each scenario in the uncertain context as many times as the values of the feasibility degree α, that is 11 times (α =0,0.1,0.2, ..., 0.9,1).

7.1.1. SC Planned Evaluation: Deterministic and Uncertain Environment

The ***SC Planned Evaluation*** is performed per each scenario under deterministic and uncertain contexts in terms of the metrics for the SC shown in Figure 3. This will allow us to determine the impact of modelling the different sources of SC uncertainty answering, therefore, to the RQ4.

As can be seen in Figure 5, the SC Planned Evaluation shows a decrease in the SC objective function and the SC margin per hectare with an increase of the feasibility degree (α-value) in all scenarios. This behaviour remains for the results for the SC in terms of the percentage of waste and the percentage of unmet demand since they get worse as the feasibility degree increases. This is because the flexibility given to the constraints where fuzzy parameters exist is bigger when the feasibility degree decreases. It should be noted that for our case study no waste exists in the distributed scenario D and DAm although waste could appear if not enough capacity exists to pack all the harvested quantities during their shelf-life. However, as commented previously, these scenarios do not consider any market demand assuming that all quantities harvested are going to be sold and, consequently, the unmet demand is zero. For this reason, waste and unmet demand take a non-null value in the planned situation only for scenarios taking into account market demand (Scenarios DIS and C). It can be also noted that workforce costs are higher for Scenarios D and DAm than scenarios DIS and C. This is because in the formers, the area of all farmers is planted and then cultivated, harvested and packed, increasing the need of laborers, meanwhile for the later only the area needed to satisfy demand is planted.

Figure 3. SC Planned Evaluation of the Deterministic and Uncertain MPM solutions for each Scenario and α-values



The fuzzy solutions outperform the deterministic ones for all scenarios, being the most similar ones when α-value is equal to one, because the closer the α-value comes to 1, the more similar the triangular fuzzy number is to the deterministic value. It is remarkable that the unfairness in the Distributed Scenarios D, DAm and DIS are similar and much lower than the Centralized Scenario C. For all the scenarios the unfairness increases with α, being the increment much more pronounced in the Centralized Scenario C. Therefore, an important finding should be pointed out: 1) the distributed scenarios provide fairer solutions than the centralized scenario and 2) to consider the uncertainty in fresh tomato SC improves the unfairness among farmers especially for the Centralized Scenario C.

On the other hand, in the planned situation, the distributed scenarios that provide better and worse results are the Scenario DAm and the Scenario DIS, respectively. The Scenario DIS is very near to Scenario C (SC Benchmark). The difference among scenarios for each α-value is quite similar but not the same for the Objective Function and Margin per ha, and very different for the remaining evaluation parameters.

7.1.2. SC Planned vs Real Evaluation: comparison for Scenarios in Deterministic and Uncertain environment

Section 7.1.1 has shown the SC planned evaluation for the solutions obtained in all distributed Scenarios. As stated before, for each distributed scenario the decisions of all farmers (solutions to their models) are put together into an auxiliary centralized model to contrast the global supply of all farmers against the market demands and, in consequence, to calculate the real value of the performance parameters. In the following, the results obtained for both the SC planned and SC real evaluations in the deterministic and uncertain contexts for each scenario are represented (Table 9). These results have been validated by the experts by whom the problem was defined in the framework of a European project. This confirms the realism, coherence, and implementability of solutions.

For the uncertain context, the planned and real evaluation corresponds to the solutions obtained solving each model with the selected α resulting from the application of the methodology of Peidró et al. (2010). The comparison between the SC Real Evaluation and SC Planned Evaluation (Real vs Planned) for the Objective Function and Margin per Hectare parameters are calculated as 100*(SC Real-SC Planned)/SC Planned. The comparison between the real values and the benchmark (Real vs Benchmark) is calculated as 100*(SC Real-SC Benchmark)/SC Benchmark.

In terms of the Objective function and the Margin per hectare, results obtained by uncertain MPMs are better than those obtained by the deterministic ones for both, real and planned situations (Table 9). When talking about the planned results, best values are obtained for Scenario D, followed by Scenario DAm and DIS, for both deterministic and uncertain solutions. However, the values for the objective function and the margin per hectare drastically decrease for the ***SC Real Evaluation*** for the two distributed scenarios not considering market demands (D, DAm) in both uncertain and deterministic contexts. The reason is that, in Scenarios D and DAm, all the farmers' area is planted assuming during the planned situation that all quantities harvested are going to be sold because any information about markets' demand is available.

Table 9. Comparison of evaluation parameters (Objective function and Margin per hectare) for planned and real situations in deterministic and uncertain context

Context	Scenario	Objective function				Margin per hectare			
		SC Planned (€)	SC Real (€)	Real vs. Planned (%)	Real vs. Benchmark (%)	Planned (€/ha)	Real (€/ha)	Real vs. Planned (%)	Real vs. Benchmark (%)
Deterministic	D	8,345,629	77,775	- 99.1	- 97.2	92,729	8,144	-91.2	-73.8
	DAm	7,859,709	1,455,119	-81.5	-47.2	87,330	20,911	-76.1	-32.8
	DIS	2,683,026	2,683,026	0.0	-2.7	30,312	30,312	0.0	-2.5
	C	2,757,388				31,103			
Uncertain	D	8,957,297	143,530	-98.4	-95.3	99,526	9,034	-90.9	-73.6
	DAm	8,550,497	1,572,606	-81.6	-48.3	95,006	22,544	-76.3	-34.1
	DIS	2,966,645	2,966,645	0.0	-2.5	33,400	33,400	0.0	-2.3
	C	3,042,017				34,190			

Table 10. Comparison of evaluation parameters (% Waste, %Unmet Demand and Unfairness) for planned and real situations in deterministic and uncertain context.

Context	Scenario	% Waste				% Unmet demand				Unfairness			
		Planned (%)	Real (%)	Real vs. Planned (%)	Real vs. Benchmark (%)	Planned (%)	Real (%)	Real vs. Planned (%)	Real vs. Benchmark (%)	Planned (%)	Real (%)	Real vs. Planned (%)	Real vs. Benchmark (%)
Deterministic	D	0.0	79.0	79.0	67.7	0.0	53.4	53.4	51.1	3.0	6.1	3.1	-53.4
	DAm	0.0	63.4	63.4	52.1	0.0	28.7	28.7	26.4	2.8	10.0	7.2	-49.5
	DIS	12.2	12.2	0.0	0.9	2.2	2.2	0.0	-0.1	3.4	3.4	0	-56.1
	C	11.3				2.3				59.5			
Uncertain	D	0.0	78.8	78.8	69.6	0.0	50.5	50.5	48.6	2.9	5.5	2.6	-51.3
	DAm	0.0	66.9	66.9	57.7	0.0	34.2	34.2	32.3	2.6	3.2	0.6	-53.6
	DIS	10.5	10.5	0.0	1.3	1.7	1.7	0.0	-0.2	3.3	3.3	0.0	-53.5
	C	9.2				1.9				56.8			

The higher the planted area, the higher the labour resources requirements and their associated costs independently of the quantities finally sold. But in real situations, when planting and harvesting decisions made by each farmer are integrated, the supply exceeds the market demand for some varieties (the most profitable ones) and stays below the market demand for other (the less profitable ones), producing waste and unmet demand, respectively, in each farmer. As can be seen in Table 16, the worsening between the planned and real value of waste and unmet demand is important.

In case of Scenario DIS planned and real results in terms of the objective function and the margin per hectare are the same because this distributed scenario also has considered market demands in the same way as the auxiliary centralized model (i.e. demands for each farmer are proportional to his/her area).

From the analysis of the ***SC Real Evaluation*** versus the ***SC Benchmark*** (Scenario C) in the deterministic context, it can be stated that the closest to the benchmark is the DIS scenario. Indeed, real solutions of DIS scenario are remarkably close to the optimum (-2.7% for the objective function and -2.5% for margin per ha) that shows the adequacy of collaboration by means the market demand information sharing. On the contrary, not taking into account market demand and any limits on planting area per variety leads to the worst situation (Scenario D). In the middle, the widespread practice of limiting the minimum and maximum area per crop significantly improves the solution obtained (Scenario DAm). The described behaviour maintains also for the uncertain results, but they always outperform the deterministic ones.

As stated before, when analysing the percentage of waste and the percentage of unmet demand obtained by each scenario and context (Table 10), it is seen that in Scenario D and DAm, neither waste nor unmet demand is produced in a planned situation because it is assumed that all produced quantities are going to be sold due to the ignorance about market demands. But when the harvested quantities of all tomato varieties for all farmers are considered to satisfy the real market demand (real evaluation), excess and shortage in supply for some periods and varieties exist provoking waste and unmet demand, respectively. In real situations, the uncertain solutions not always outperform deterministic solutions as regards the evaluation parameters %Waste and %Unmet Demand. In case of Scenario DIS planned and real results in terms of the percentage of waste and unmet demand are the same, and they are also quite similar to the results obtained for the benchmark.

Finally, the **Unfairness** among farmers is analysed. For all distributed scenarios in both deterministic and uncertain contexts, except for the Scenario DIS, the real unfairness increases in comparison with the planned one, but the difference is very much higher for the deterministic solution (7.2% vs 0.6%). Despite this, the solutions obtained for the distributed scenarios are all very much fairer than those obtained from the Centralized Scenario because its objective function maximizes the profit of the entire SC but does not balance the profits among farmers.

It is concluded that given the similarity of the objective function, margin per hectare, percentage of waste and unmet demand between Scenarios DIS and C, and given the good results in terms of unfairness that Scenario DIS provides, it is a good solution for the AFSC to maintain the independence of the farmers by using a distributed model where minimal information of the markets demand proportional to the farmers' area is included and only shared with a central coordinator (Scenario DIS).

7.1.4. Experimental Results: Computational Efficiency

All MPM models have been implemented in the MPL® 5.0 modelling language, solved with the Gurobi 8.0.1, and Microsoft Access databases were used. The computer used had an Intel® Xeon® CPU E5-2640 v2 with two 2.00 GHz processor, with an installed capacity of 32.0 GB and a 64-bits operating system.

The resolution time for each model execution was limited to 60 min. A relative gap of 0.02% was fixed. This means that the solution search process can stop if a solution is found to be within 0.02% of the best bound before the 60 min has elapsed. Such solution would be the optimal solution to the problem. Table 11 shows for each Scenario the number of executions made, the percentage of optimal solutions found (gap lower than 0.02%), and the mean time needed to find these optimal solutions. As it can be seen, the number of models solved (executions) in the deterministic context for the distributed scenarios equals the number of farmers (10), meanwhile, for the uncertain context, the model for each farmer should be solved for the 11 α-values, that is 110 times (10 farmers*11 α-values). For the centralized Scenario C, only 1 execution is enough in the deterministic context and 11 executions in the uncertain context.

These results show that optimal solutions have been obtained for all the distributed Scenarios (Percentage of optimal solutions of 100%). In the case of Scenario C, the optimal solution has not been found in any execution within the resolution time limit of 60 min (Percentage of optimal solutions of 0%) although the gaps obtained are extremely small: 0.0386% and 0.0424% for the deterministic and uncertain environment, respectively. In planned situations, the resolution time is lower for the deterministic models than for the uncertain models in all distributed Scenarios (D, DAm, and DIS). The same occurs to the relative gap of Scenario C since it is larger for the uncertain model than for the deterministic one. When jointly analysing all Scenarios for the planned situation, it seems that the more complex model is the one related to Scenario C, followed by the model designed for Scenario DIS, DAm, and D.

Table 11. Resolution time and relative gap per Scenario and context.

Context	Scenario	Number of executions	Percentage of optimal solutions	Mean solution time	Mean GAP for non-optimum solutions
Deterministic	D	10	100%	3.5 sec	-
	DAm	10	100%	6.7 sec	-
	DIS	10	100%	1 min 35 sec	-
	C	1	0%	60 min 00 sec	0.0386 %
Uncertain	D	110	100%	5.2 sec	-
	DAm	110	100%	8.6 sec	-
	DIS	110	100%	4 min 13 sec	-
	C	11	0%	60 min 00 sec	0.0424 %

The problem size is analysed in terms of the number of continuous, integer, and binary variables, and the number of constraints (Table 12). As can be seen, the number of decision variables is higher for DIS due to the unmet demand and sales variables and for C because of the integration of all farmers. Finally, the number of constraints increases in an uncertain context. These two aspects justify the increase in the solution time for DIS and C and for the uncertain context as regards the deterministic one.

Table 12. Problem size per scenario and context.

Scenario	Total variables	Continuous variables	Integer variables	Binary variables	Constraints	
					Deterministic	Uncertain
D	8,350	5,064	3,247	39	12,731	13,364
DAm	8,350	5,064	3,247	39	17,737	13,370
DIS	11,194	7,908	3,247	39	33,093	34,038
C	109,132	76,272	32,470	390	325,626	333,828

8. Conclusions and future research lines

To match the supply and demand of crops is not an easy task due to the great sources of uncertainty affecting the agricultural sector that mainly impacts on the supply, demand, and market prices that originates high volumes of waste and unmet demand. This problem is accentuated by the individuality of farmers leading to a distributed decision-making scenario. Although this way of organization is frequent, the vast majority of the developed MPMs to support the crop planning problem are developed only for one farmer. When contemplating several farmers, a centralized decision-making supported by a single MPM without neither collaboration nor mechanism to ensure a fair solution among farmers is usually proposed.

In this paper, a novel set of MPMs for the cropping plan problem of fresh tomato supply chain integrated by independent farmers in a deterministic and uncertain context has been developed in several scenarios. Several MPMs in the literature for supporting the crop planning problem for individual farmers do not consider any market demand assuming that all the harvested quantities are going to be sold in the market. As shown in this paper, in the absence of other limitations, this way of making decisions (Scenario D) lead to plant all the land area only with the most profitable crops by all farmers provoking an excessive amount of waste for some crops and high levels of unmet demand for the others when the global production is put in the market. The negative impact of this solution can be measured not only in economic losses for farmers that can see a great decrease in their expected profits, but also in social terms (unmet demand) and environmental (crop waste, resources losses, and unnecessarily cultivated land area).

To mitigate these negative effects and the risk faced by farmers, a widespread custom consists in limiting the maximum and minimum land area planted per crop. This corresponds to Scenario DAm that define the limits based on a proportional crop margin percentage of the land area allocated to each crop. As shown, the values set for these upper and lower limits highly impact on solutions obtained but, again, surprisingly, no attention has been paid in the literature to fix their value. In this scenario, the planned results also get worse in real situations when integrating production by all farmers against market demand but the negative impact on economic losses, waste, and unmet demand is lower than in Scenario D.

The best results for the SC in real situations are achieved by the centralized decision-making situation (Scenario C) where market demand is known. Though this scenario gets the optimum SC solution as regards the objective function, it provides the most unfair solution among farmers. Therefore, unless an only company exists in the SC some mechanisms should be introduced to reach a fair solution. Furthermore, in most cases, the atomized structure of farmers in some regions make a centralized approach impossible to be implemented.

A collaborative approach that consists of information sharing about the market demand is proposed, respecting the independence among farmers and therefore, the distributed decision-making. This organizational structure can fit in many situations in which some public associations advise farmers about what to do (e.g., commerce chamber, regional innovation, and technological centres). In this situation, the adviser association can know the land area of each farmer and also the forecast market demands calculating a proportional demand to be faced by each farmer based on his/her land area. With this information, farmers make their planting and harvesting decisions. As shown in this paper, this collaboration approach based on information sharing (Scenario DIS), leads to results very close to the optimal SC solution provided by the centralized MPM (Scenario C) and the best fair solution, what encourages farmers to follow it. Therefore, the concrete way of Scenario DIS for collaboration among producers with minimum information sharing leads to a mutually beneficial cooperation that improves farmers' incomes and their position in the value chain, as well as benefits consumers whose demands will be satisfied at more stable prices.

Finally, the obtained results show that the modelling of uncertainty improves the margin per hectare and the unfairness among farmers in all scenarios, meanwhile, the waste and the unmet demand do not present a homogeneous behaviour in all scenarios.

Future research lines as regards the MPM models developed can consider the uncertainty in the planting, cultivating, and harvesting periods due to weather conditions. The model could be extended to incorporate other crops that can be planted more than once in a season. Finally, the models could be extended to incorporate the processing stage with particular attention paid to the fair distribution of costs, profits, and risks among all actors involved in the agri-food value chains in order to improve the position of small farmers.

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Appendix A – MPM for all farmers in the Centralized Scenario C

In the following table, the definition part of the model for the centralized Scenario C is presented.

Table A.1. Nomenclature for the Centralized Model of Scenario C.

Indices			
v	Tomato variety	t	Time period in general
p	Planting period	f	Farmer
h	Harvest period	m	Market
w	Harvesting patterns		
Set of indices			
P_v	Set of planting dates p in which tomatoes of variety v can be planted.		
H_v^p	Set of harvest dates h that correspond to each planting date p and tomato variety v		
PS_v^t	Set of planting dates p for tomato variety v that requires stake up activities at t		
PC_v^t	Set of planting dates p for tomato variety v that requires pruning activities at t		
PK_v^t	Set of planting dates p for tomato variety v that requires phytosanitary application at t		
PH_v^h	Set of planting dates p for tomato variety v that enables harvest at h		
Parameters			
$\tilde{p}_{vm}^t$	Selling price for each tomato variety v at market m and period t (€/kg)		
$\widetilde{de}_{vm}^t$	Demand of the tomato variety v at market m and period t (kg)		
cf_v	Cost per plant and cultivate one plant of tomato variety v (€/planta).		
$\widetilde{cwa}_v$	Penalty cost for wasting one kilogram of variety tomato v after harvest (€/kg)		
ct_{vfm}	Cost of packing and transporting one kilogram of tomato variety v from farmer f to market m (€/kg)		
ch_v	Unitary holding cost of tomato variety v per period (€/kg·week)		
$\widetilde{cud}_{vm}$	Penalty cost for not fulfilling one kilogram of tomato variety v at market m (€/kg)		
chs	Cost of hiring one seasonal worker (€)		
cls	Cost per period for one seasonal worker (€/week)		
clt	Cost per period for one temporary worker (€/week)		
a_f	Available area for planting tomatoes at farmer f (ha)		
d_v	Density of cultivation of variety of tomato v (plants/ha)		
$amin_v$	Minimum area to be planted per period and variety, in case the variety is decided to be planted (ha) due to technical aspects (no managerial aspects)		
$\tilde{y}_{vw}^{ph}$	Quantity of tomatoes obtained from a plant of variety v at period h if planted at period p (kg/plant)		
$\widetilde{tp}_v$	Time needed to plant one tomato plant of variety v (min/plant)		
$\widetilde{ts}_v$	Time needed per period to stake up one tomato plant of variety v (min/plant)		
$\widetilde{tc}_v$	Time needed per period to prune one tomato plant of variety v (min/plant)		
$\widetilde{tk}_v$	Time needed per period to apply phytosanitary products in one plant of variety v (min/plant)		
$\widetilde{th}_{vw}$	Time needed to harvest a tomato plant of variety v under pattern w (min/plant)		
$\widetilde{tpa}_v$	Time needed to pack one kilogram of tomato of variety v (min/kg)		
sl_v^{ph}	Shelf-life of tomato variety v if planted at period p and harvested in period h (week)		
hw	Available capacity per worker in a period (min/week)		
$MinLS_f$	Minimum number of seasonal workers per period at farm f		
$MaxLS$	Maximum number of seasonal workers per period		
$MaxLT$	Maximum number of temporary workers per period		
Decision variable			
NP_{vf}^p	Number of plants of tomato variety v planted at period p by the farmer f (plant)		
YP_{vf}^p	Binary variable with a value of 1 if tomato variety v is planted by the farmer f at planting date p, and with a value of 0, otherwise.		
NS_{vf}^t	Number of plants of tomato variety v to be staked and strung up by the farmer f at period t (plant)		

NC_{vf}^{t}	Number of plants of tomato variety v to be pruned by the farmer f at period t (plant)
NK_{vf}^{t}	Number of plants of tomato variety v that require the application of phytosanitary products by the farmer f at period t (plant)
NHW_{vfw}^{ph}	Number of plants of tomato variety v planted by farmer f in period p to be harvested in period h by pattern w (plant)
QH_{vf}^{ph}	Quantity of tomato variety v harvested by farmer f at period h from plants planted at p (kg)
WAH_{vf}^{ph}	Quantity of tomato of variety v planted by farmer f at planting period p and wasted at the farm level after harvest at period h (kg). This waste is produced by the tomatoes harvested not transported to markets.
QP_{vf}^{pht}	Quantity of tomato of variety v planted at planting period p, harvested at period h and packed by farmer f at period t (kg).
QT_{vfm}^{pht}	Quantity of tomato of variety v planted at planting period p, harvested at period h and transported from farmer f to market m at period t (kg).
QS_{vfm}^{pht}	Quantity of tomatoes variety v planted in farm f at period p, harvested at h and sold at period t at market m (kg)
UD_{vm}^{t}	Quantity of unmet demand of tomato variety v at period t in market m (kg)
HLS_{f}^{t}	Number of seasonal laborers hired by farmer f at period t
LS_{f}^{t}	Number of seasonal laborers working at farm f at period t
FLS_{f}^{t}	Number of seasonal laborers fired by farmer f at period t
LT_{f}^{t}	Number of temporary laborers working at farm f at period t
Pr	Profit obtained by the region (€)

The objective function (A.1) tries to maximize the profits of the region calculated as the difference between the incomes per sales in different markets and the total costs.

$$\begin{aligned} Max\ Pr = & \sum_{v}\sum_{f}\sum_{m}\sum_{p\in P_v}\sum_{h\in H_v^p}\sum_{t}\tilde{p}_{vm}^{t}\cdot QS_{vfm}^{pht} - \sum_{v}\sum_{f}\sum_{p\in P_v} cf_v \cdot NP_{vf}^{p} \\ & - \sum_{v}\sum_{f}\sum_{m}\sum_{p\in P_v}\sum_{h\in H_v^p}\sum_{t} ch_v\cdot (t-h)\cdot QT_{vfm}^{pht} \\ & - \sum_{v}\sum_{f}\sum_{p\in P_v}\sum_{h\in H_v^p}\widetilde{cwa}_v\cdot WAH_{vf}^{ph} - \sum_{v}\sum_{f}\sum_{m}\sum_{p\in P_v}\sum_{h\in H_v^p}\sum_{t} ct_{vfm}\cdot QT_{vfm}^{pht} \\ & - \sum_{v}\sum_{m}\sum_{t}\widetilde{cud}_{vm}\cdot UD_{vm}^{t} - \sum_{f}\sum_{t}\left(chs\cdot HLS_f^t + cls\cdot LS_f^t + clt\cdot LT_f^t\right) \end{aligned} \quad (A.1)$$

$Subject\ to$:

$$\sum_{v}\sum_{p\in P_v}\frac{NP_{vf}^{p}}{d_v} \le a_f \qquad \forall f \quad (A.2)$$

$$\frac{NP_{vf}^{p}}{d_v} \ge amin_v \cdot YP_{vf}^{p} \qquad \forall v, f, p \in P_v \quad (A.3)$$

$$\frac{NP_{vf}^{p}}{d_v} \le a_f \cdot YP_{vf}^{p} \qquad \forall v, f, p \in P_v \quad (A.4)$$

$$NS_{vf}^{t} = \sum_{p\in PS_v^t} NP_{vf}^{p} \qquad \forall v, f, t \quad (A.5)$$

$$NC_{vf}^{t} = \sum_{p \in PC_v^t} NP_{vf}^{p} \qquad \forall v, f, t \tag{A.6}$$

$$NK_{vf}^{t} = \sum_{p \in PK_v^t} NP_{vf}^{p} \qquad \forall v, f, t \tag{A.7}$$

$$\sum_{w} NHW_{vfw}^{ph} = NP_{vf}^{p} \qquad \forall v, f, h, p \in PH_v^h \tag{A.8}$$

$$\sum_{w} \tilde{y}_{vw}^{ph} \cdot NHW_{vfw}^{ph} = QH_{vf}^{ph} \qquad \forall v, f, p \in P_v, h \in H_v^p \tag{A.9}$$

$$QH_{vf}^{ph} = \sum_{m} \sum_{h \le t \le h + sl_v^{ph}} QT_{vfm}^{pht} + WAH_{vf}^{ph} \qquad \forall v, f, p \in P_v, h \in H_v^p \tag{A.10}$$

$$QP_{vf}^{pht} = \sum_{m} QT_{vfm}^{pht} \qquad \forall v, f, p \in P_v, h \in H_v^p, t \ge h \tag{A.11}$$

$$QT_{vfm}^{pht} = QS_{vfm}^{pht} \qquad \forall v, f, m, p \in P_v, h \in H_v^p, t \ge h \tag{A.12}$$

$$\sum_{f} \sum_{p \in P_v} \sum_{h \in H_v^p} QS_{vfm}^{pht} + UD_{vm}^{t} = \widetilde{de}_{vm}^{t} \qquad \forall v, m, t \tag{A.13}$$

$$\begin{aligned} &\sum_{v} \sum_{p=t} \widetilde{tp}_v \cdot NP_{vf}^{p} + \sum_{v} \widetilde{ts}_v \cdot NS_{vf}^{t} + \sum_{v} \widetilde{tc}_v \cdot NC_{vf}^{t} + \sum_{v} \widetilde{tk}_v \cdot NK_{vf}^{t} \\ &\quad + \sum_{v} \sum_{p \in P_v} \sum_{w} \sum_{h=t} \widetilde{th}_{vw} \cdot NHW_{vfw}^{ph} + \sum_{v} \sum_{p \in P_v} \sum_{h \in H_v^p} \widetilde{tpa}_v \cdot QP_{vf}^{pht} \\ &\quad \le hw \cdot \left(LS_f^t + LT_f^t \right) \quad \forall f, t \end{aligned} \tag{A.14}$$

$$LS_f^t = LS_f^{t-1} + HLS_f^t - FLS_f^t \qquad \forall f, t \tag{A.15}$$

$$MinLS_f \le LS_f^t \qquad \forall f, t \tag{A.16}$$

$$\sum_{f} LT_f^t \le MaxLT \qquad \forall t \tag{A.17}$$

$$\sum_{f} LS_f^t \le MaxLS \qquad \forall t \tag{A.18}$$

$$\begin{gathered} Pr, QH_{vf}^{ph}, QP_{vf}^{pht}, QT_{vfm}^{pht}, QS_{vfm}^{pht}, WAH_{vf}^{ph}, UD_{vm}^{t} \quad CONTINUOUS \\ NP_{vf}^{p}, NS_{vf}^{t}, NC_{vf}^{t}, NK_{vf}^{t}, NHW_{vfw}^{ph}, HLS_f^t, LS_f^t, FLS_f^t, LT_f^t \quad INTEGER \\ YP_{v_f}^{p} \quad BINARY \end{gathered} \tag{A.19}$$

Constraints (A.2) to (A.11) are similar to constraints (2) to (11) of Scenario D, respectively, with the difference of including the index f to distinguish among farmers. The quantities transported coincide with the quantities sold for each tomato variety, farmer, and period (A.12) similar to (20) in the DIS model. This means that not waste can be produced in markets, because it is more economic waste the product immediately after harvest than after being transported. Set of constraints (A.13) oblige the total quantity sold by all farmers plus the unmet demand at each market in a period *t* to be equal to the demand of each tomato variety at that market and period. Through this set of constraints, the global quantity sold will be never higher than the demand, and, in the case of being lower, the unmet demand per variety, market, and period is computed. Set of constraints (A.14) and (A.15) are similar to (12) and (13) but including the index *f* for each farmer. As the other scenarios, a minimum number of seasonal workers must work at each farm and period (A.16) but in the Centralized Scenario C, the maximum available temporary (A.17) and seasonal workers are limited for all the region (A.18), respectively (see the sum in *f*). The set of constraints (A.19) defines the nature of the decision variables

Appendix B – Equivalent α-parametric crisp models

In this Appendix, the fuzzy models developed for each scenario in Section 4 are converted into the equivalent α-parametric crisp models by applying the methodology of Jimenez (1996).

B.1. Distributed Models for each Farmer under Scenario D

$$Max\ PrF = \sum_{v}\sum_{m}\sum_{p\in P_v}\sum_{h\in H_v^p}\sum_{t}\left(\frac{p_{vm}^{t^1}+p_{vm}^{t^2}+p_{vm}^{t^3}+p_{vm}^{t^4}}{4}\right)\cdot QTF_{vm}^{pht} - \sum_{v}\sum_{p\in P_v} cf_v\cdot NPF_v^p - \sum_{v}\sum_{m}\sum_{p\in P_v}\sum_{h\in H_v^p}\sum_{t} ctF_{vm}\cdot QTF_{vm}^{pht} - \sum_{v}\sum_{m}\sum_{p\in P_v}\sum_{h\in H_v^p}\sum_{t} ch_v\cdot(t-h)\cdot QTF_{vm}^{pht} - \sum_{v}\sum_{p\in P_v}\sum_{h\in H_v^p}\left(\frac{cwa_v^1+cwa_v^2+cwa_v^3+cwa_v^4}{4}\right)\cdot WAHF_v^{ph} - \sum_{t}(chs\cdot HLSF^t + cls\cdot LSF^t + clt\cdot LTF^t) \quad \text{(B.1)}$$

$Subject\ to$

$$\sum_{w}\left[\left(1-\frac{\alpha}{2}\right)\cdot\left(\frac{y_{vw}^{ph^1}+y_{vw}^{ph^2}}{2}\right)+\left(\frac{\alpha}{2}\right)\cdot\left(\frac{y_{vw}^{ph^3}+y_{vw}^{ph^4}}{2}\right)\right]\cdot NHWF_{vw}^{ph} - QHF_v^{ph} \le 0 \qquad \forall v,p \in P_v, h\in H_v^p \quad \text{(B.2)}$$

$$\sum_{w}\left[\left(1-\frac{\alpha}{2}\right)\cdot\left(\frac{y_{vw}^{ph^3}+y_{vw}^{ph^4}}{2}\right)+\left(\frac{\alpha}{2}\right)\cdot\left(\frac{y_{vw}^{ph^1}+y_{vw}^{ph^2}}{2}\right)\right]\cdot NHWF_{vw}^{ph} - QHF_v^{ph} \ge 0 \quad \forall v,p \in P_v, h\in H_v^p \quad \text{(B.3)}$$

$$\sum_{v}\sum_{p=t}\left[(1-\alpha)\cdot\left(\frac{tp_v^1+tp_v^2}{2}\right)+\alpha\cdot\left(\frac{tp_v^3+tp_v^4}{2}\right)\right]\cdot NPF_v^p + \sum_{v}\left[(1-\alpha)\cdot\left(\frac{ts_v^1+ts_v^2}{2}\right)+\alpha\cdot\left(\frac{ts_v^3+ts_v^4}{2}\right)\right]\cdot NSF_v^t + \sum_{v}\left[(1-\alpha)\cdot\left(\frac{tc_v^1+tc_v^2}{2}\right)+\alpha\cdot\left(\frac{tc_v^3+tc_v^4}{2}\right)\right]\cdot NCF_v^t + \sum_{v}\left[(1-\alpha)\cdot\left(\frac{tk_v^1+tk_v^2}{2}\right)+\alpha\cdot\left(\frac{tk_v^3+tk_v^4}{2}\right)\right]\cdot NKF_v^t + \sum_{v}\sum_{w}\sum_{p\in P_v}\sum_{h=t}\left[(1-\alpha)\cdot\left(\frac{th_{vw}^1+th_{vw}^2}{2}\right)+\alpha\cdot\left(\frac{th_{vw}^3+th_{vw}^4}{2}\right)\right]\cdot NHWF_{vw}^{ph} + \sum_{v}\sum_{p\in P_v}\sum_{h\in H_v^p}\left[(1-\alpha)\cdot\left(\frac{tpa_v^1+tpa_v^2}{2}\right)+\alpha\cdot\left(\frac{tpa_v^3+tpa_v^4}{2}\right)\right]\cdot QPF_v^{pht} \le hw\cdot(LS^t+LT^t) \quad \forall t \quad \text{(B.4)}$$

(2)-(8), (10), (11), (13-16)

B.2. Distributed Models for each Farmer under Scenario DAm

$Max\ PrF$ (B.5)

$Subject\ to$

$$\sum_{p\in P_v}\frac{NPF_v^p}{d_v} \ge \left[\alpha\cdot\left(\frac{am_v^3+am_v^4}{2}\right)+(1-\alpha)\cdot\left(\frac{am_v^1+am_v^2}{2}\right)\right] \qquad \forall v \quad \text{(B.6)}$$

$$\sum_{p\in P_v}\frac{NPF_v^p}{d_v}\leq\left[\alpha\cdot\left(\frac{aM_v^1+aM_v^2}{2}\right)+(1-\alpha)\cdot\left(\frac{aM_v^3+aM_v^4}{2}\right)\right]\qquad\forall v \tag{B.7}$$

(2)-(8), (10), (11), (13-16), (B.2)-(B.4)

B.3. Distributed Models for each Farmer under Scenario DIS

$$\begin{aligned}PrF=&\sum_v\sum_m\sum_{p\in P_v}\sum_{h\in H_v^p}\sum_t\left(\frac{p_{vm}^{t^1}+p_{vm}^{t^2}+p_{vm}^{t^3}+p_{vm}^{t^4}}{4}\right)\cdot QTF_{vm}^{pht}-\sum_v\sum_f\sum_{p\in P_v}cf_v\cdot NPF_v^p\\&-\sum_v\sum_m\sum_{p\in P_v}\sum_{h\in H_v^p}\sum_t ctF_{vm}\cdot QTF_{vm}^{pht}\\&-\sum_v\sum_m\sum_{p\in P_v}\sum_{h\in H_v^p}\sum_t ch_v\cdot(t-h)\cdot QTF_{vm}^{pht}\\&-\sum_t(chs\cdot HLSF^t+cls\cdot LSF^t+clt\cdot LTF^t)\\&-\sum_v\sum_{p\in P_v}\sum_{h\in H_v^p}\left(\frac{cwa_v^1+cwa_v^2+cwa_v^3+cwa_v^4}{4}\right)\cdot WAHF_v^{ph}\\&-\sum_v\sum_m\sum_t\left(\frac{cud_{vm}^1+cud_{vm}^2+cud_{vm}^3+cud_{vm}^4}{4}\right)\cdot UD_{vm}^t\end{aligned}\tag{B.8}$$

Subject to

$$\sum_{p\in P_v}\sum_{h\in H_v^p}QSF_{vm}^{pht}+UD_{vm}^t\leq\left(\frac{\alpha}{2}\right)\cdot\left(\frac{deF_{vm}^{t^1}+deF_{vm}^{t^2}}{2}\right)+\left(1-\frac{\alpha}{2}\right)\cdot\left(\frac{deF_{vm}^{t^3}+deF_{vm}^{t^4}}{2}\right)\qquad\forall v,m,t \tag{B.9}$$

$$\sum_{p\in P_v}\sum_{h\in H_v^p}QSF_{vm}^{pht}+UD_{vm}^t\geq\left(\frac{\alpha}{2}\right)\cdot\left(\frac{deF_{vm}^{t^3}+deF_{vm}^{t^4}}{2}\right)+\left(1-\frac{\alpha}{2}\right)\cdot\left(\frac{deF_{vm}^{t^1}+deF_{vm}^{t^2}}{2}\right)\qquad\forall v,m,t \tag{B.10}$$

(2)-(8), (10), (11), (13-16), (20), (22), (B.2)-(B.4)

A.4. Centralized Model for Scenario C

$$\begin{aligned}Max\ Pr=&\sum_v\sum_f\sum_m\sum_{p\in P_v}\sum_{h\in H_v^p}\sum_t\left(\frac{p_{vm}^{t^1}+p_{vm}^{t^2}+p_{vm}^{t^3}+p_{vm}^{t^4}}{4}\right)\cdot QS_{vfm}^{pht}\\&-\sum_v\sum_f\sum_{p\in P_v}cf_v\cdot NP_{vf}^p-\sum_v\sum_f\sum_m\sum_{p\in P_v}\sum_{h\in H_v^p}\sum_t ct_{vfm}\cdot QT_{vfm}^{pht}\\&-\sum_v\sum_f\sum_m\sum_{p\in P_v}\sum_{h\in H_v^p}\sum_t ch_v\cdot(t-h)\cdot QT_{vfm}^{pht}\\&-\sum_f\sum_t\left(chs\cdot HLS_f^t+cls\cdot LS_f^t+clt\cdot LT_f^t\right)\\&-\sum_v\sum_f\sum_{p\in P_v}\sum_{h\in H_v^p}\left(\frac{cwa_v^1+cwa_v^2+cwa_v^3+cwa_v^4}{4}\right)\cdot WAH_{vf}^{ph}\\&-\sum_v\sum_m\sum_t\left(\frac{cud_{vm}^1+cud_{vm}^2+cud_{vm}^3+cud_{vm}^4}{4}\right)\cdot UD_{vm}^t\end{aligned}\tag{B.11}$$

Subject to

$$\sum_w\left[\left(1-\frac{\alpha}{2}\right)\cdot\left(\frac{y_{vw}^{ph^1}+y_{vw}^{ph^2}}{2}\right)+\left(\frac{\alpha}{2}\right)\cdot\left(\frac{y_{vw}^{ph^3}+y_{vw}^{ph^4}}{2}\right)\right]\cdot NHW_{vfw}^{ph}-QH_{vf}^{ph}\leq 0\qquad\forall v,f,p\in P_v,h\in H_v^p \tag{B.12}$$

$$\sum_{w}\left[\left(1-\frac{\alpha}{2}\right)\cdot\left(\frac{y_{vw}^{ph^3}+y_{vw}^{ph^4}}{2}\right)+\left(\frac{\alpha}{2}\right)\cdot\left(\frac{y_{vw}^{ph^1}+y_{vw}^{ph^2}}{2}\right)\right]\cdot NHW_{vfw}^{ph}-QH_{vf}^{ph}\geq 0 \tag{B.13}$$

$$\forall v,f,p\in P_v,h\in H_v^p$$

$$\sum_{f}\sum_{p\in P_v}\sum_{h\in H_v^p}QS_{vfm}^{pht}+UD_{vm}^{t}\leq\left(\frac{\alpha}{2}\right)\cdot\left(\frac{de_{vm}^{t^1}+de_{vm}^{t^2}}{2}\right)+\left(1-\frac{\alpha}{2}\right)\cdot\left(\frac{de_{vm}^{t^3}+de_{vm}^{t^4}}{2}\right) \tag{B.14}$$

$$\forall v,m,t$$

$$\sum_{f}\sum_{p\in P_v}\sum_{h\in H_v^p}QS_{vfm}^{pht}+UD_{vm}^{t}\geq\left(\frac{\alpha}{2}\right)\cdot\left(\frac{de_{vm}^{t^3}+de_{vm}^{t^4}}{2}\right)+\left(1-\frac{\alpha}{2}\right)\cdot\left(\frac{de_{vm}^{t^1}+de_{vm}^{t^2}}{2}\right) \tag{B.15}$$

$$\forall v,m,t$$

$$\begin{aligned}\sum_{v}\sum_{p=t}&\left[(1-\alpha)\cdot\left(\frac{tp_v^1+tp_v^2}{2}\right)+\alpha\cdot\left(\frac{tp_v^3+tp_v^4}{2}\right)\right]\cdot NP_{vf}^{p}\\
&+\sum_{v}\left[(1-\alpha)\cdot\left(\frac{ts_v^1+ts_v^2}{2}\right)+\alpha\cdot\left(\frac{ts_v^3+ts_v^4}{2}\right)\right]\cdot NS_{vf}^{t}\\
&+\sum_{v}\left[(1-\alpha)\cdot\left(\frac{tc_v^1+tc_v^2}{2}\right)+\alpha\cdot\left(\frac{tc_v^3+tc_v^4}{2}\right)\right]\cdot NC_{vf}^{t}\\
&+\sum_{v}\left[(1-\alpha)\cdot\left(\frac{tk_v^1+tk_v^2}{2}\right)+\alpha\cdot\left(\frac{tk_v^3+tk_v^4}{2}\right)\right]\cdot NK_{vf}^{t}\\
&+\sum_{v}\sum_{w}\sum_{p\in P_v}\sum_{h=t}\left[(1-\alpha)\cdot\left(\frac{th_{vw}^1+th_{vw}^2}{2}\right)+\alpha\cdot\left(\frac{th_{vw}^3+th_{vw}^4}{2}\right)\right]\\
&\cdot NHW_{vfw}^{ph}\\
&+\sum_{v}\sum_{p\in P_v}\sum_{h\in H_v^p}\left[(1-\alpha)\cdot\left(\frac{tpa_v^1+tpa_v^2}{2}\right)+\alpha\cdot\left(\frac{tpa_v^3+tpa_v^4}{2}\right)\right]\cdot QP_{vf}^{pht}\\
&\leq hw\cdot\left(LS_f^t+LT_f^t\right)\quad\forall t\end{aligned} \tag{B.16}$$

(A.2)-(A.8), (A.10)-(A.12), (A.15-A.19)

Appendix C. Problem Data Description

The tomato supply chain under consideration integrated by ten farmers located in four different regions of La Plata (Buenos Aires) and two markets (Central Market of Buenos Aires and Restaurants). The land area for each farmer and the entire SC, as well as data regarding workers for manual labour, can be consulted in Table C.1.

The cost for a seasonal worker is 42.5 €/week, for a temporary worker is 69 €/week and for hiring seasonal workers 42.5€.

Table C.1. Land area and data of workers per farmer and for the whole SC

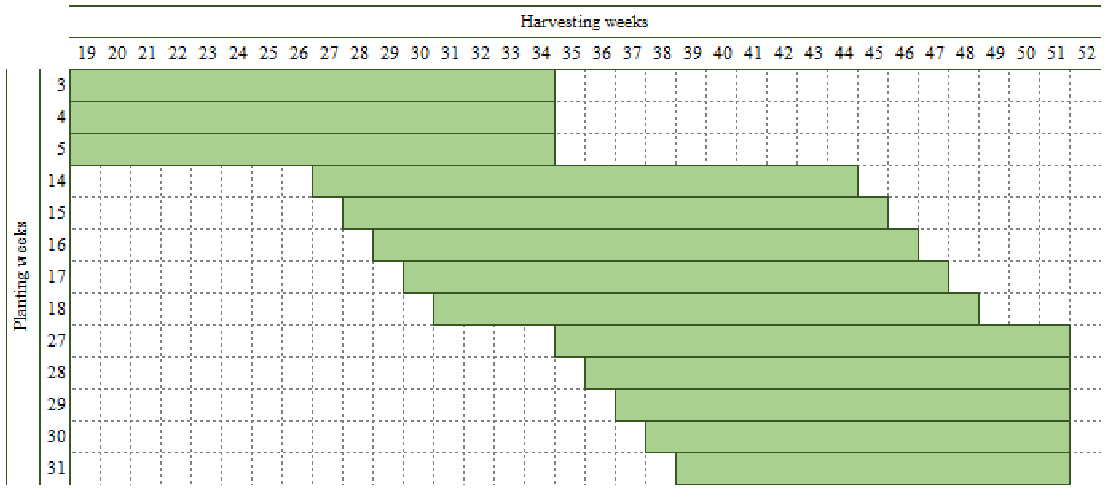
Farmers	1	2	3	4	5	6	7	8	9	10	SC
Land area (ha)	8.9	7.1	6.2	8.5	9.8	10.7	11.6	8	8.5	10.7	90
Seasonal workers (minimum)	4	4	3	4	5	5	6	4	4	5	44
Seasonal workers (maximum)	7	6	5	7	8	9	9	6	8	9	74
Temporary workers (maximum)	2	2	2	2	2	3	3	2	2	3	23

Farmers should decide the allocation of their greenhouses area to three varieties of tomato: round, pear, and cherry. The minimum ($\widetilde{am}_v$) and maximum ($\widetilde{aM}_v$) land area per tomato variety is obtained as follows. The mean gross margin is calculated summing up the price of each period and market for each tomato variety and divided by the sum of the mean gross margins for all varieties. The obtained percentage for each crop variety is multiplied by 1.1 and 0.9 for defining the upper and lower percentages, respectively, providing the following values for each variety: round tomato [40%, 49%], pear tomato [38%, 47%], cherry tomato [12%, 14%]. These percentages are multiplied by the total land area of each farmer obtaining the parameters $\widetilde{am}_v$ and $\widetilde{aM}_v$, respectively.

We assume that our planning horizon comprises a whole planting season of one year divided into 52 weeks. The planting year is considered to start in the first week of July (t=1) being the planting and harvesting calendar the same for the three tomato varieties. There are three planting seasons in July (weeks 3 to 5), October (weeks 14 to 18), and

January (27 to 31). The harvesting period comprises several consecutive weeks that are dependent on the week the tomato had been planted (Figure C.1).

Figure C.1. Planting and harvesting calendar for all three tomato varieties



The operation times per tomato variety appear in Table C.2. As Ahumada & Villalobos (2011b) we consider four harvesting patterns: pattern I (harvest every day), pattern II (harvest every two days), pattern III (harvest three times per week), and pattern IV (harvest two times per week). The time to harvest one tomato plant depends on the harvesting pattern (Table C.2) meanwhile the yield per plant of each tomato variety depends additionally on the planting and harvest period (Appendix D).

Table C.2. Cultivating, harvesting, and packaging times for each tomato variety.

Tomato variety		Round	Pear	Cherry
Time to plant one plant (min/plant)		0.10909	0.10909	0.12632
Time to stake up one plant (min/plant·week)		0.17455	0.17455	0.20211
Time to prune one plant (min/plant·week)		0.06109	0.06109	0.07074
Time to apply phytosanitary products (min/plant·week)		0.00809	0.00809	0.00937
Time to harvest (min/plant)	Pattern I	0.06818	0.06818	0.15789
	Pattern II	0.06136	0.06136	0.14211
	Pattern III	0.05455	0.05455	0.12632
	Pattern IV	0.04773	0.04773	0.11025
Time to pack tomatoes (min/kg)		0.20000	0.20000	0.20000

Inventory costs per week are calculated as the 1% of the maximum price of the year for each tomato variety. The tomato shelf-life once harvested for all varieties is assumed to be one week. The penalization for the wasted kilograms is calculated as the

5% of the maximum price for each tomato variety during the year. The penalization for each kg of unmet demand is the 4.5% of the maximum price for each tomato variety and market (Table 12). Cultivation density can also be consulted in Table C.3.

Table C.3. Relevant costs, penalties, and density for each tomato variety.

Tomato variety	Holding cost (€/kg·week)	Planting and cultivating cost (€/plant)	Waste penalties (€/kg)	Cultivation density (plants/ha)	Unmet demand penalties (€/kg)	
					Central market	Restaurants
Round	0.010	0.033	0.052	22,000	0.018	0.047
Pear	0.010	0.033	0.052	22,000	0.022	0.047
Cherry	0.017	0.033	0.092	19,000	0.060	0.083

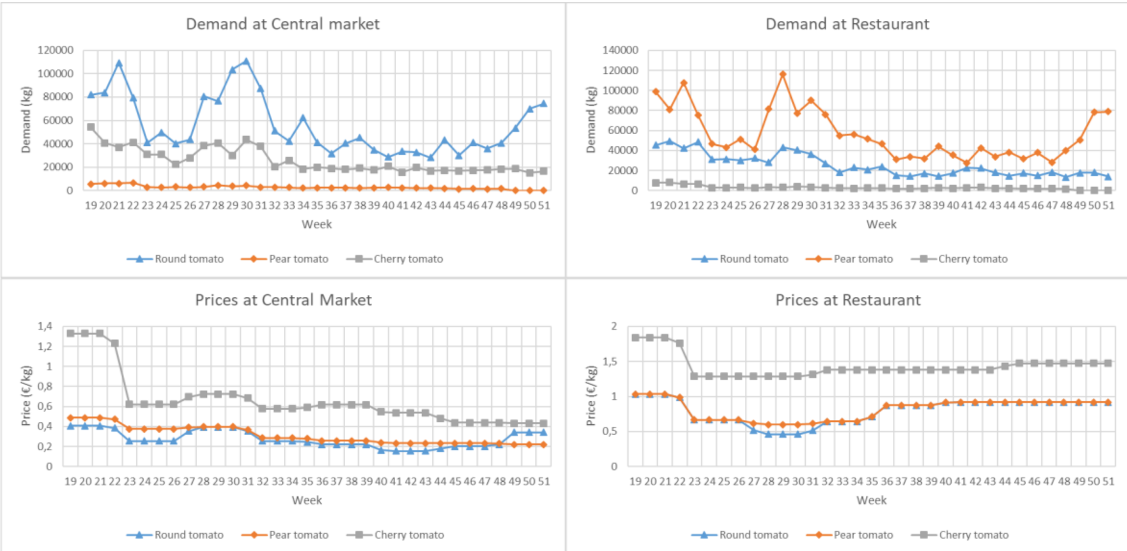
It is assumed that farmers are physically located in four different regions of La Plata being the transportation costs between farmers and different markets the same for the farmers belonging to the same region due to little distances among them (Table C.4).

Table C.4. Transport costs per market and region farmers belong to.

Transport costs (€/ka)				Transport costs (€/ka)			
Region	Farmer	Market		Region	Farmer	Market	
		Central market	Restaurants			Central market	Restaurants
A	1	0.238	0.431	C	6	0.281	0.333
	2	0.238	0.431		7	0.281	0.333
B	3	0.283	0.329	D	8	0.169	0.218
	4	0.283	0.329		9	0.169	0.218
	5	0.283	0.329		10	0.169	0.218

Figure C.2. represents the demand and prices per variety of tomato and market. The demand data has been generated by randomly varying the last year's supply of the different tomato varieties. Only the demand for harvesting periods has been considered because the demand for the remaining periods of the year is covered by external supply. Market prices have been obtained from the website of the Central Market of Buenos Aires where prices for end consumers and prices for wholesalers (in this case, restaurants) are published. As it can be observed, the prices for restaurants (retailers) are higher than in Central Market (wholesalers) because the sales in restaurants are more expensive in terms of transport (see Table C.4.) and order preparation.

Figure C.2. Demand (kg) and Prices (€/kg) per tomato variety and market.



Uncertain MPM parameters are modelled as triangular fuzzy numbers (TFN) represented by $\tilde{b} = (b_1, b_2, b_3)$ for which the most possible value (b_2) coincides with the deterministic one and the most pessimistic and optimistic value, except for the selling price, are calculated by decreasing and increasing a fixed percentage of b_2 . This percentage is different for each uncertain parameter and is based on the decision-maker knowledge. The percentage for the time needed to plant, stake up, prune, apply phytosanitary products, harvest tomato plants, and pack tomatoes is set to 15%; for the demand to 35%; for the yield of the crops to 30%; for the minimum and maximum areas to be planted to 10% and for waste and unmet demand penalties to 20%. Finally, the most possible value for the selling prices per tomato variety and period is defined by the price used in the deterministic context that corresponds to the prices of last year. For defining the most pessimistic value, the maximum between the minimum price allowed for each tomato variety and the 70% of the most possible value is chosen. The minimum prices can be consulted in Table C.5., not being possible to sell tomatoes below them in the corresponding markets. The most optimistic value is obtained by increasing in 40% the most possible value. For this parameter, the membership function is not represented with an isosceles triangle. Depending on the period, the triangle will vary.

Table C.5. Minimum market prices allowed for each tomato variety.

Tomato variety	Minimum prices (€/kg)	
	Central market	Restaurants
Round	0.13	0.23
Pear	0.22	0.57
Cherry	0.35	1.15

Appendix D. Plant yield per tomato variety along the horizon

Figure D.1. Plant yield (kg/plant) of the round tomato depending on the planting date, harvesting date, and harvesting pattern.

Suma de y	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Redondo																															
I																															
3	0,227	0,397	0,397	0,434	0,660	0,660	0,660	0,660	0,552	0,508	0,508	0,508	0,444	0,284	0,284	0,162															
4	0,227	0,397	0,397	0,434	0,660	0,660	0,660	0,660	0,552	0,508	0,508	0,508	0,444	0,284	0,284	0,162															
5	0,227	0,397	0,397	0,434	0,660	0,660	0,660	0,660	0,552	0,508	0,508	0,508	0,444	0,284	0,284	0,162															
14									0,181	0,253	0,253	0,253	0,356	0,613	0,613	0,613	0,549	0,391	0,391	0,391	0,391	0,176	0,140	0,140	0,140	0,060					
15										0,181	0,253	0,253	0,253	0,356	0,613	0,613	0,613	0,549	0,391	0,391	0,391	0,391	0,176	0,140	0,140	0,140	0,060				
16											0,181	0,253	0,253	0,253	0,356	0,613	0,613	0,613	0,549	0,391	0,391	0,391	0,391	0,176	0,140	0,140	0,140	0,060			
17												0,181	0,253	0,253	0,253	0,356	0,613	0,613	0,613	0,549	0,391	0,391	0,391	0,391	0,176	0,140	0,140	0,140	0,060		
18													0,181	0,253	0,253	0,253	0,356	0,613	0,613	0,613	0,549	0,391	0,391	0,391	0,391	0,176	0,140	0,140	0,140	0,060	
27																	0,066	0,230	0,230	0,230	0,230	0,503	0,548	0,548	0,548	0,436	0,352	0,352	0,352	0,329	0,191
28																		0,066	0,230	0,230	0,230	0,230	0,503	0,548	0,548	0,548	0,436	0,352	0,352	0,352	0,329
29																			0,066	0,230	0,230	0,230	0,230	0,503	0,548	0,548	0,548	0,436	0,352	0,352	0,352
30																				0,066	0,230	0,230	0,230	0,230	0,503	0,548	0,548	0,548	0,436	0,352	0,352
31																					0,066	0,230	0,230	0,230	0,230	0,503	0,548	0,548	0,548	0,436	0,352
II																															
3	0,204	0,357	0,357	0,391	0,594	0,594	0,594	0,594	0,496	0,457	0,457	0,457	0,400	0,255	0,255	0,146															
4	0,204	0,357	0,357	0,391	0,594	0,594	0,594	0,594	0,496	0,457	0,457	0,457	0,400	0,255	0,255	0,146															
5	0,204	0,357	0,357	0,391	0,594	0,594	0,594	0,594	0,496	0,457	0,457	0,457	0,400	0,255	0,255	0,146															
14									0,163	0,228	0,228	0,228	0,320	0,551	0,551	0,551	0,494	0,352	0,352	0,352	0,352	0,158	0,126	0,126	0,126	0,054					
15										0,163	0,228	0,228	0,228	0,320	0,551	0,551	0,551	0,494	0,352	0,352	0,352	0,352	0,158	0,126	0,126	0,126	0,054				
16											0,163	0,228	0,228	0,228	0,320	0,551	0,551	0,551	0,494	0,352	0,352	0,352	0,352	0,158	0,126	0,126	0,126	0,054			
17												0,163	0,228	0,228	0,228	0,320	0,551	0,551	0,551	0,494	0,352	0,352	0,352	0,352	0,158	0,126	0,126	0,126	0,054		
18													0,163	0,228	0,228	0,228	0,320	0,551	0,551	0,551	0,494	0,352	0,352	0,352	0,352	0,158	0,126	0,126	0,126	0,054	
27																	0,059	0,207	0,207	0,207	0,207	0,453	0,494	0,494	0,494	0,393	0,317	0,317	0,317	0,296	0,172
28																		0,059	0,207	0,207	0,207	0,207	0,453	0,494	0,494	0,494	0,393	0,317	0,317	0,317	0,296
29																			0,059	0,207	0,207	0,207	0,207	0,453	0,494	0,494	0,494	0,393	0,317	0,317	0,317
30																				0,059	0,207	0,207	0,207	0,207	0,453	0,494	0,494	0,494	0,393	0,317	0,317
31																					0,059	0,207	0,207	0,207	0,207	0,453	0,494	0,494	0,494	0,393	0,317
III																															
3	0,181	0,317	0,317	0,347	0,528	0,528	0,528	0,528	0,441	0,406	0,406	0,406	0,355	0,227	0,227	0,130															
4	0,181	0,317	0,317	0,347	0,528	0,528	0,528	0,528	0,441	0,406	0,406	0,406	0,355	0,227	0,227	0,130															
5	0,181	0,317	0,317	0,347	0,528	0,528	0,528	0,528	0,441	0,406	0,406	0,406	0,355	0,227	0,227	0,130															
14									0,145	0,202	0,202	0,202	0,285	0,490	0,490	0,490	0,439	0,313	0,313	0,313	0,313	0,141	0,112	0,112	0,112	0,048					
15										0,145	0,202	0,202	0,202	0,285	0,490	0,490	0,490	0,439	0,313	0,313	0,313	0,313	0,141	0,112	0,112	0,112	0,048				
16											0,145	0,202	0,202	0,202	0,285	0,490	0,490	0,490	0,439	0,313	0,313	0,313	0,313	0,141	0,112	0,112	0,112	0,048			
17												0,145	0,202	0,202	0,202	0,285	0,490	0,490	0,490	0,439	0,313	0,313	0,313	0,313	0,141	0,112	0,112	0,112	0,048		
18													0,145	0,202	0,202	0,202	0,285	0,490	0,490	0,490	0,439	0,313	0,313	0,313	0,313	0,141	0,112	0,112	0,112	0,048	
27																	0,053	0,184	0,184	0,184	0,184	0,402	0,439	0,439	0,439	0,349	0,282	0,282	0,282	0,263	0,153
28																		0,053	0,184	0,184	0,184	0,184	0,402	0,439	0,439	0,439	0,349	0,282	0,282	0,282	0,263
29																			0,053	0,184	0,184	0,184	0,184	0,402	0,439	0,439	0,439	0,349	0,282	0,282	0,282
30																				0,053	0,184	0,184	0,184	0,184	0,402	0,439	0,439	0,439	0,349	0,282	0,282
31																					0,053	0,184	0,184	0,184	0,184	0,402	0,439	0,439	0,439	0,349	0,282
IV																															
3	0,159	0,278	0,278	0,304	0,462	0,462	0,462	0,462	0,386	0,356	0,356	0,356	0,311	0,198	0,198	0,113															
4	0,159	0,278	0,278	0,304	0,462	0,462	0,462	0,462	0,386	0,356	0,356	0,356	0,311	0,198	0,198	0,113															
5	0,159	0,278	0,278	0,304	0,462	0,462	0,462	0,462	0,386	0,356	0,356	0,356	0,311	0,198	0,198	0,113															
14									0,126	0,177	0,177	0,177	0,249	0,429	0,429	0,429	0,384	0,273	0,273	0,273	0,273	0,123	0,098	0,098	0,098	0,042					
15										0,126	0,177	0,177	0,177	0,249	0,429	0,429	0,429	0,384	0,273	0,273	0,273	0,273	0,123	0,098	0,098	0,098	0,042				
16											0,126	0,177	0,177	0,177	0,249	0,429	0,429	0,429	0,384	0,273	0,273	0,273	0,273	0,123	0,098	0,098	0,098	0,042			
17												0,126	0,177	0,177	0,177	0,249	0,429	0,429	0,429	0,384	0,273	0,273	0,273	0,273	0,123	0,098	0,098	0,098	0,042		
18													0,126	0,177	0,177	0,177	0,249	0,429	0,429	0,429	0,384	0,273	0,273	0,273	0,273	0,123	0,098	0,098	0,098	0,042	
27																	0,046	0,161	0,161	0,161	0,161	0,352	0,384	0,384	0,384	0,305	0,247	0,247	0,247	0,230	0,134
28																		0,046	0,161	0,161	0,161	0,161	0,352	0,384	0,384	0,384	0,305	0,247	0,247	0,247	0,230
29																			0,046	0,161	0,161	0,161	0,161	0,352	0,384	0,384	0,384	0,305	0,247	0,247	0,247
30																				0,046	0,161	0,161	0,161	0,161	0,352	0,384	0,384	0,384	0,305	0,247	0,247
31																					0,046	0,161	0,161	0,161	0,161	0,352	0,384	0,384	0,384	0,305	0,247

Figure D.2. Plant yield (kg/plant) of the pear tomato depending on the planting date, harvesting date, and harvesting pattern.

Suma de y	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	4
Pera																															
I																															
3	0,214	0,374	0,374	0,400	0,559	0,559	0,559	0,559	0,490	0,462	0,462	0,462	0,399	0,242	0,242	0,138															
4	0,214	0,374	0,374	0,400	0,559	0,559	0,559	0,559	0,490	0,462	0,462	0,462	0,399	0,242	0,242	0,138															
5	0,214	0,374	0,374	0,400	0,559	0,559	0,559	0,559	0,490	0,462	0,462	0,462	0,399	0,242	0,242	0,138															
14									0,161	0,226	0,226	0,226	0,327	0,580	0,580	0,580	0,514	0,349	0,349	0,349	0,349	0,160	0,128	0,128	0,128	0,055					
15										0,161	0,226	0,226	0,226	0,327	0,580	0,580	0,580	0,514	0,349	0,349	0,349	0,349	0,160	0,128	0,128	0,128	0,055				
16											0,161	0,226	0,226	0,226	0,327	0,580	0,580	0,580	0,514	0,349	0,349	0,349	0,349	0,160	0,128	0,128	0,128	0,055			
17												0,161	0,226	0,226	0,226	0,327	0,580	0,580	0,580	0,514	0,349	0,349	0,349	0,349	0,160	0,128	0,128	0,128	0,055		
18													0,161	0,226	0,226	0,226	0,327	0,580	0,580	0,580	0,514	0,349	0,349	0,349	0,349	0,160	0,128	0,128	0,128	0,055	
27																	0,060	0,209	0,209	0,209	0,209	0,486	0,532	0,532	0,532	0,416	0,328	0,328	0,328	0,307	0,18
28																		0,060	0,209	0,209	0,209	0,209	0,486	0,532	0,532	0,532	0,416	0,328	0,328	0,328	0,30
29																			0,060	0,209	0,209	0,209	0,209	0,486	0,532	0,532	0,532	0,416	0,328	0,328	0,32
30																				0,060	0,209	0,209	0,209	0,209	0,486	0,532	0,532	0,532	0,416	0,328	0,32
31																					0,060	0,209	0,209	0,209	0,209	0,486	0,532	0,532	0,532	0,416	0,32
II																															
3	0,192	0,336	0,336	0,360	0,503	0,503	0,503	0,503	0,441	0,416	0,416	0,416	0,359	0,218	0,218	0,124															
4	0,192	0,336	0,336	0,360	0,503	0,503	0,503	0,503	0,441	0,416	0,416	0,416	0,359	0,218	0,218	0,124															
5	0,192	0,336	0,336	0,360	0,503	0,503	0,503	0,503	0,441	0,416	0,416	0,416	0,359	0,218	0,218	0,124															
14									0,145	0,203	0,203	0,203	0,294	0,522	0,522	0,522	0,462	0,314	0,314	0,314	0,314	0,144	0,116	0,116	0,116	0,050					
15										0,145	0,203	0,203	0,203	0,294	0,522	0,522	0,522	0,462	0,314	0,314	0,314	0,314	0,144	0,116	0,116	0,116	0,050				
16											0,145	0,203	0,203	0,203	0,294	0,522	0,522	0,522	0,462	0,314	0,314	0,314	0,314	0,144	0,116	0,116	0,116	0,050			
17												0,145	0,203	0,203	0,203	0,294	0,522	0,522	0,522	0,462	0,314	0,314	0,314	0,314	0,144	0,116	0,116	0,116	0,050		
18													0,145	0,203	0,203	0,203	0,294	0,522	0,522	0,522	0,462	0,314	0,314	0,314	0,314	0,144	0,116	0,116	0,116	0,050	
27																	0,054	0,188	0,188	0,188	0,188	0,438	0,479	0,479	0,479	0,374	0,296	0,296	0,296	0,277	0,16
28																		0,054	0,188	0,188	0,188	0,188	0,438	0,479	0,479	0,479	0,374	0,296	0,296	0,296	0,27
29																			0,054	0,188	0,188	0,188	0,188	0,438	0,479	0,479	0,479	0,374	0,296	0,296	0,29
30																				0,054	0,188	0,188	0,188	0,188	0,438	0,479	0,479	0,479	0,374	0,296	0,29
31																					0,054	0,188	0,188	0,188	0,188	0,438	0,479	0,479	0,479	0,374	0,29
III																															
3	0,171	0,299	0,299	0,320	0,448	0,448	0,448	0,448	0,392	0,370	0,370	0,370	0,319	0,193	0,193	0,111															
4	0,171	0,299	0,299	0,320	0,448	0,448	0,448	0,448	0,392	0,370	0,370	0,370	0,319	0,193	0,193	0,111															
5	0,171	0,299	0,299	0,320	0,448	0,448	0,448	0,448	0,392	0,370	0,370	0,370	0,319	0,193	0,193	0,111															
14									0,129	0,181	0,181	0,181	0,261	0,464	0,464	0,464	0,411	0,279	0,279	0,279	0,279	0,128	0,103	0,103	0,103	0,044					
15										0,129	0,181	0,181	0,181	0,261	0,464	0,464	0,464	0,411	0,279	0,279	0,279	0,279	0,128	0,103	0,103	0,103	0,044				
16											0,129	0,181	0,181	0,181	0,261	0,464	0,464	0,464	0,411	0,279	0,279	0,279	0,279	0,128	0,103	0,103	0,103	0,044			
17												0,129	0,181	0,181	0,181	0,261	0,464	0,464	0,464	0,411	0,279	0,279	0,279	0,279	0,128	0,103	0,103	0,103	0,044		
18													0,129	0,181	0,181	0,181	0,261	0,464	0,464	0,464	0,411	0,279	0,279	0,279	0,279	0,128	0,103	0,103	0,103	0,044	
27																	0,048	0,168	0,168	0,168	0,168	0,389	0,426	0,426	0,426	0,333	0,263	0,263	0,263	0,246	0,14
28																		0,048	0,168	0,168	0,168	0,168	0,389	0,426	0,426	0,426	0,333	0,263	0,263	0,263	0,24
29																			0,048	0,168	0,168	0,168	0,168	0,389	0,426	0,426	0,426	0,333	0,263	0,263	0,26
30																				0,048	0,168	0,168	0,168	0,168	0,389	0,426	0,426	0,426	0,333	0,263	0,26
31																					0,048	0,168	0,168	0,168	0,168	0,389	0,426	0,426	0,426	0,333	0,26
IV																															
3	0,150	0,262	0,262	0,280	0,392	0,392	0,392	0,392	0,343	0,323	0,323	0,323	0,279	0,169	0,169	0,097															
4	0,150	0,262	0,262	0,280	0,392	0,392	0,392	0,392	0,343	0,323	0,323	0,323	0,279	0,169	0,169	0,097															
5	0,150	0,262	0,262	0,280	0,392	0,392	0,392	0,392	0,343	0,323	0,323	0,323	0,279	0,169	0,169	0,097															
14									0,113	0,158	0,158	0,158	0,229	0,406	0,406	0,406	0,360	0,244	0,244	0,244	0,244	0,112	0,090	0,090	0,090	0,039					
15										0,113	0,158	0,158	0,158	0,229	0,406	0,406	0,406	0,360	0,244	0,244	0,244	0,244	0,112	0,090	0,090	0,090	0,039				
16											0,113	0,158	0,158	0,158	0,229	0,406	0,406	0,406	0,360	0,244	0,244	0,244	0,244	0,112	0,090	0,090	0,090	0,039			
17												0,113	0,158	0,158	0,158	0,229	0,406	0,406	0,406	0,360	0,244	0,244	0,244	0,244	0,112	0,090	0,090	0,090	0,039		
18													0,113	0,158	0,158	0,158	0,229	0,406	0,406	0,406	0,360	0,244	0,244	0,244	0,244	0,112	0,090	0,090	0,090	0,039	
27																	0,042	0,147	0,147	0,147	0,147	0,340	0,373	0,373	0,373	0,291	0,230	0,230	0,230	0,215	0,12
28																		0,042	0,147	0,147	0,147	0,147	0,340	0,373	0,373	0,373	0,291	0,230	0,230	0,230	0,21
29																			0,042	0,147	0,147	0,147	0,147	0,340	0,373	0,373	0,373	0,291	0,230	0,230	0,23
30																				0,042	0,147	0,147	0,147	0,147	0,340	0,373	0,373	0,373	0,291	0,230	0,23
31																					0,042	0,147	0,147	0,147	0,147	0,340	0,373	0,373	0,373	0,291	0,23

Figure D.3. Plant yield (kg/plant) of the cherry tomato depending on the planting date, harvesting date, and harvesting pattern.

Suma de y	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	
⊟Cherry																															
⊟I																															
3	0,098	0,172	0,172	0,175	0,191	0,191	0,191	0,191	0,150	0,133	0,133	0,133	0,150	0,192	0,192	0,109															
4	0,098	0,172	0,172	0,175	0,191	0,191	0,191	0,191	0,150	0,133	0,133	0,133	0,150	0,192	0,192	0,109															
5	0,098	0,172	0,172	0,175	0,191	0,191	0,191	0,191	0,150	0,133	0,133	0,133	0,150	0,192	0,192	0,109															
14									0,081	0,113	0,113	0,113	0,139	0,203	0,203	0,203	0,185	0,143	0,143	0,143	0,143	0,129	0,126	0,126	0,126	0,054					
15										0,081	0,113	0,113	0,113	0,139	0,203	0,203	0,203	0,185	0,143	0,143	0,143	0,143	0,129	0,126	0,126	0,126	0,054				
16											0,081	0,113	0,113	0,113	0,139	0,203	0,203	0,203	0,185	0,143	0,143	0,143	0,143	0,129	0,126	0,126	0,126	0,054			
17												0,081	0,113	0,113	0,113	0,139	0,203	0,203	0,203	0,185	0,143	0,143	0,143	0,143	0,129	0,126	0,126	0,126	0,054		
18													0,081	0,113	0,113	0,113	0,139	0,203	0,203	0,203	0,185	0,143	0,143	0,143	0,143	0,129	0,126	0,126	0,126	0,054	
27																	0,004	0,015	0,015	0,015	0,015	0,153	0,176	0,176	0,176	0,191	0,203	0,203	0,203	0,174	
28																		0,004	0,015	0,015	0,015	0,015	0,153	0,176	0,176	0,176	0,191	0,203	0,203	0,203	0,[illegible]
29																			0,004	0,015	0,015	0,015	0,015	0,153	0,176	0,176	0,176	0,191	0,203	0,203	0,[illegible]
30																				0,004	0,015	0,015	0,015	0,015	0,153	0,176	0,176	0,176	0,191	0,203	0,[illegible]
31																					0,004	0,015	0,015	0,015	0,015	0,153	0,176	0,176	0,176	0,191	0,[illegible]
⊟II																															
3	0,088	0,155	0,155	0,157	0,172	0,172	0,172	0,172	0,135	0,120	0,120	0,120	0,135	0,172	0,172	0,099															
4	0,088	0,155	0,155	0,157	0,172	0,172	0,172	0,172	0,135	0,120	0,120	0,120	0,135	0,172	0,172	0,099															
5	0,088	0,155	0,155	0,157	0,172	0,172	0,172	0,172	0,135	0,120	0,120	0,120	0,135	0,172	0,172	0,099															
14									0,073	0,102	0,102	0,102	0,125	0,182	0,182	0,182	0,167	0,128	0,128	0,128	0,128	0,116	0,114	0,114	0,114	0,049					
15										0,073	0,102	0,102	0,102	0,125	0,182	0,182	0,182	0,167	0,128	0,128	0,128	0,128	0,116	0,114	0,114	0,114	0,049				
16											0,073	0,102	0,102	0,102	0,125	0,182	0,182	0,182	0,167	0,128	0,128	0,128	0,128	0,116	0,114	0,114	0,114	0,049			
17												0,073	0,102	0,102	0,102	0,125	0,182	0,182	0,182	0,167	0,128	0,128	0,128	0,128	0,116	0,114	0,114	0,114	0,049		
18													0,073	0,102	0,102	0,102	0,125	0,182	0,182	0,182	0,167	0,128	0,128	0,128	0,128	0,116	0,114	0,114	0,114	0,049	
27																	0,004	0,013	0,013	0,013	0,013	0,137	0,158	0,158	0,158	0,172	0,183	0,183	0,183	0,157	
28																		0,004	0,013	0,013	0,013	0,013	0,137	0,158	0,158	0,158	0,172	0,183	0,183	0,183	0,[illegible]
29																			0,004	0,013	0,013	0,013	0,013	0,137	0,158	0,158	0,158	0,172	0,183	0,183	0,[illegible]
30																				0,004	0,013	0,013	0,013	0,013	0,137	0,158	0,158	0,158	0,172	0,183	0,[illegible]
31																					0,004	0,013	0,013	0,013	0,013	0,137	0,158	0,158	0,158	0,172	0,[illegible]
⊟III																															
3	0,079	0,138	0,138	0,140	0,153	0,153	0,153	0,153	0,120	0,106	0,106	0,106	0,120	0,153	0,153	0,088															
4	0,079	0,138	0,138	0,140	0,153	0,153	0,153	0,153	0,120	0,106	0,106	0,106	0,120	0,153	0,153	0,088															
5	0,079	0,138	0,138	0,140	0,153	0,153	0,153	0,153	0,120	0,106	0,106	0,106	0,120	0,153	0,153	0,088															
14									0,065	0,090	0,090	0,090	0,111	0,162	0,162	0,162	0,148	0,114	0,114	0,114	0,114	0,103	0,101	0,101	0,101	0,043					
15										0,065	0,090	0,090	0,090	0,111	0,162	0,162	0,162	0,148	0,114	0,114	0,114	0,114	0,103	0,101	0,101	0,101	0,043				
16											0,065	0,090	0,090	0,090	0,111	0,162	0,162	0,162	0,148	0,114	0,114	0,114	0,114	0,103	0,101	0,101	0,101	0,043			
17												0,065	0,090	0,090	0,090	0,111	0,162	0,162	0,162	0,148	0,114	0,114	0,114	0,114	0,103	0,101	0,101	0,101	0,043		
18													0,065	0,090	0,090	0,090	0,111	0,162	0,162	0,162	0,148	0,114	0,114	0,114	0,114	0,103	0,101	0,101	0,101	0,043	
27																	0,003	0,012	0,012	0,012	0,012	0,122	0,141	0,141	0,141	0,153	0,162	0,162	0,162	0,139	
28																		0,003	0,012	0,012	0,012	0,012	0,122	0,141	0,141	0,141	0,153	0,162	0,162	0,162	0,[illegible]
29																			0,003	0,012	0,012	0,012	0,012	0,122	0,141	0,141	0,141	0,153	0,162	0,162	0,[illegible]
30																				0,003	0,012	0,012	0,012	0,012	0,122	0,141	0,141	0,141	0,153	0,162	0,[illegible]
31																					0,003	0,012	0,012	0,012	0,012	0,122	0,141	0,141	0,141	0,153	0,[illegible]
⊟IV																															
3	0,069	0,120	0,120	0,122	0,134	0,134	0,134	0,134	0,105	0,093	0,093	0,093	0,105	0,134	0,134	0,077															
4	0,069	0,120	0,120	0,122	0,134	0,134	0,134	0,134	0,105	0,093	0,093	0,093	0,105	0,134	0,134	0,077															
5	0,069	0,120	0,120	0,122	0,134	0,134	0,134	0,134	0,105	0,093	0,093	0,093	0,105	0,134	0,134	0,077															
14									0,056	0,079	0,079	0,079	0,097	0,142	0,142	0,142	0,130	0,100	0,100	0,100	0,100	0,090	0,089	0,089	0,089	0,038					
15										0,056	0,079	0,079	0,079	0,097	0,142	0,142	0,142	0,130	0,100	0,100	0,100	0,100	0,090	0,089	0,089	0,089	0,038				
16											0,056	0,079	0,079	0,079	0,097	0,142	0,142	0,142	0,130	0,100	0,100	0,100	0,100	0,090	0,089	0,089	0,089	0,038			
17												0,056	0,079	0,079	0,079	0,097	0,142	0,142	0,142	0,130	0,100	0,100	0,100	0,100	0,090	0,089	0,089	0,089	0,038		
18													0,056	0,079	0,079	0,079	0,097	0,142	0,142	0,142	0,130	0,100	0,100	0,100	0,100	0,090	0,089	0,089	0,089	0,038	
27																	0,003	0,010	0,010	0,010	0,010	0,107	0,123	0,123	0,123	0,134	0,142	0,142	0,142	0,122	
28																		0,003	0,010	0,010	0,010	0,010	0,107	0,123	0,123	0,123	0,134	0,142	0,142	0,142	0,[illegible]
29																			0,003	0,010	0,010	0,010	0,010	0,107	0,123	0,123	0,123	0,134	0,142	0,142	0,[illegible]
30																				0,003	0,010	0,010	0,010	0,010	0,107	0,123	0,123	0,123	0,134	0,142	0,[illegible]
31																					0,003	0,010	0,010	0,010	0,010	0,107	0,123	0,123	0,123	0,134	0,[illegible]