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Optimization model to support sustainable crop planning for reducing unfairness among farmers

Esteso, A

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1 **Collaborative Models to Define Sustainable Crop Planning Reducing**
2 **the Unfairness among Farmers in an Uncertain Context**

3 Ana Esteso^{a*}, MME Alemany^a, Angel Ortiz^{a*} and Shaofeng Liu^b

4 *^aResearch Centre on Production Management and Engineering (CIGIP), Universitat*
5 *Politécnica de València, Camino de Vera S/N, 46022 València, Spain; ^bPlymouth*
6 *Business School, University of Plymouth, Plymouth, UK*

7 *Corresponding author: Ana Esteso: aesteso@cigip.upv.es

8 M.M.E. Alemany: mareva@omp.upv.es

9 Ángel Ortiz: aortiz@cigip.upv.es

10 Shaofeng Liu: shaofeng.liu@plymouth.ac.uk

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12 Collaborative Models to Define Sustainable Crop Planning Reducing 13 the Unfairness among Farmers in an Uncertain Context

14 Inherent uncertainty surrounding the agri-food sector negatively impacts the
15 supply chain's (SC) sustainability and performance. A main consequence of this
16 uncertainty is the imbalance between supply and demand with volatility in prices
17 and high quantities of waste and unmet demand. Usually, farmers are the most
18 affected by the negative impact of uncertainty. To improve their competitive
19 position, it is necessary to implement new business models that encourage the
20 collaboration among farms, try to reduce the number of intermediaries between
21 farms and markets, reduce the activities related to the management of perishable
22 crops and their associated costs, and enable mechanisms to sell the oversupply of
23 crops such as their settlement. In this paper, a novel multi-objective model is
24 proposed to support the crop planning under uncertainty for the proposed
25 business model. Three objectives aligned with the triple bottom lines are
26 considered: SC profit maximization (economic), waste minimization
27 (environmental) and unfairness minimization (social). The last objective reduces
28 the unwillingness of farms to cooperate with the crop planning. The model is
29 solved with the weighted sum method and compared to an equivalent model
30 considering only economic objectives, concluding that environmental and social
31 aspects can be highly improved by little decreasing profits.

32 Keywords: sustainability; collaboration; crop planning; unfairness; fuzzy multi-
33 objective model

34 1 Introduction

35 A new business model is arising in the agri-food sector that seeks to serve customers
36 that appreciate freshness and quality of products and are aware of sustainability. In this

37 business model, channels are characterized to be more direct (fewer intermediary
38 actors). The value chain proposes value to the customer by looking at previous concepts
39 and, at the same time, reducing the unfairness among farmers through a better
40 distribution of costs and benefits according to the farmer's key resources. In this
41 business model, it is very important to balance supply and demand in order to reduce
42 waste in every farmer and the unmet demand. To achieve this balance, it is necessary to
43 consider the demand during the crop planning decision-making process, which is the
44 core of farming system management. Crop planning consists in choosing the crops to be
45 planted, their acreage and their allocation to the farmland (Dury et al., 2012). Crop
46 planning decisions will determine future harvest and flow of crops along the chain, and
47 therefore their supply. However, it is not possible to reach a perfect balance between
48 demand and supply given the impact of uncertainty on both elements. These sources of
49 uncertainty inherent to the agri-food sector jointly with others negatively impact on the
50 agri-food supply chain's performance and sustainability (Esteso et al. 2018).

51 Another aspect that leads to this imbalance is that crop planning decisions are
52 usually made independently by each farmer once per season. This way of making
53 decisions usually contributes to the overproduction of the crops that were more
54 profitable on last season, leading to the drop down of prices and the production of
55 wastes. On the opposite, this produces scarcity in the supply of crops that appeared to be
56 less profitable on last season when compared to their demand, leading to the increase of
57 their prices. Collaboration mechanisms can be used when making the crop planning
58 decisions to better balance supply and demand, reducing waste and unmet demand, and
59 to protect the supply chain against the negative impact of uncertainty (Esteso et al.
60 2018). Zaraté et al. (2019) conclude that research on coordination issues in agricultural
61 SCs is in its early development. Besides Handayati et al. (2015) state in their review that

62 studies on supply chain coordination in agri-food sector with a particular focus on
63 small-scale farmers is very scarce. One collaboration mechanism applicable to the crop
64 planning problem is the decision synchronization that consists in jointly making
65 planning and operational decisions for all farms (Simatupang and Sridharan, 2005) in a
66 centralized manner.

67 To the best of our knowledge, there are no model-based computerized tools
68 to support the crop planning decisions in this new business model. It seems obvious that
69 models for crop planning should consider the demand of crops to balance supply and
70 demand, however few papers do it. In addition, most of these papers only model
71 decisions related to the crop planning such as the selection of crops to plant, the
72 definition of the area or plots allocated to each crop and decisions about the resources
73 needed to plant and cultivate the planted areas such as the irrigation, labouring, and the
74 use of fertilizers.

75 However, to balance supply and demand it is necessary to take into account
76 more operative decisions. However, few papers as well as this paper take into account
77 additional more operative decisions such as the harvest, transport and sale of crops in
78 order to anticipate the balance between supply and demand at markets (Ahumada et al.,
79 2012; Ahumada and Villalobos, 2011a, 2011b; Flores et al., 2019; Flores and
80 Villalobos, 2018; Mason and Villalobos, 2015; Najafabadi et al., 2019; Nguyen et al.,
81 2019). In the particular case of transport decisions, analysed models do not take into
82 account neither the capacity of vehicles nor the minimum cargo to be filled in order to
83 use a vehicle, which determines the quantity of vehicles necessary to transport crops
84 and limits the quantity of crops to be transported ready to satisfy demand. This paper
85 models all these aspects, filling the gap identified in literature.

86 Most models for crop planning considering the demand of crops such as the
87 proposed by Cid-Garcia and Ibarra-Rojas (2019) and Ren et al. (2019) assume that all
88 demand should be met, allowing, and not penalizing the overproduction of crops and
89 assume that all production is sold. However, few papers model what happens when
90 an imbalance between supply and demand occurs, such as the generation of
91 waste in cases of overproduction (Hasuike et al., 2018; Mason and Villalobos, 2015) or
92 unmet demand in cases of underproduction (Albornoz et al., 2020; Darby-Dowman et
93 al., 2000; dos Santos et al., 2010; Flores and Villalobos, 2018; Forrester et al., 2018;
94 Hasuike et al., 2018; Mason and Villalobos, 2015; Nguyen et al., 2019; Villa et al.,
95 2019). Furthermore, waste is also generated due to the limited shelf-life of crops that
96 has been modelled in few models (Ahumada and Villalobos, 2011a, 2011b). None of
97 the papers allowing the crops overproduction implements mechanisms to reduce wastes
98 generated along the chain by the excess of product and its perishable nature. With this
99 objective this paper, that models the over and underproduction of crops due to the
100 uncertainty in both supply and demand, proposes to settle the excess of supply at each
101 period in order to reduce the quantity of generated waste and promote the sale of fresh
102 products.

103 Given the perishability of crops and the impact that the allocated land area and
104 planting period of crops have on harvesting, and consequently, in the future available
105 supply, it is also important to take into account the multi-period nature of the problem
106 when addressing the harvesting and distribution decisions jointly with the cropping plan
107 ones to satisfy the also seasonal market demand. This aspect is even more crucial when
108 limited capacity of resources per period exist for implementing more operative
109 decisions being necessary to efficiently plan their use.

110 All the above papers propose centralized models to support the aforementioned
111 decision-making processes. Although centralized decision making process is proved to
112 provide the best results for the entire agri-food supply chain (Stadtler, 2009), obtained
113 solution would be difficult to implement in a real agri-food supply chain unless all lands
114 belong to the same farmer since centralized decision making produces inequalities
115 among the supply chain members (Ertogral and Wu, 2000) leading to the unwillingness
116 of farms to collaborate. Because of this, analysed models could not be used to solve the
117 crop planning problem in the new business model where the reduction of the unfairness
118 among farmers is essential.

119 Besides, analysed models mainly optimize economic aspects, leaving out the
120 environmental and social aspects of sustainability which is another fundamental
121 characteristic of this new business model. However, some of the analysed models
122 optimize objectives related to more than one aspect of sustainability. For example,
123 Adekanmbi and Olugbara (2015) who maximize the supply chain profits (economic)
124 while minimizing the land use (environmental). Najafabadi et al. (2019)
125 consider the three aspects of sustainability by maximizing the supply chain profits
126 (economic) while minimizing the water consumption, and the use of fertilizers and
127 pesticides (environmental) and maximizing employment and food safety (social). The
128 rest of the models to support crop planning problem analysed in this section only
129 optimized economic objectives. It is remarkable that none of these models considered
130 the reduction of wastes and unfairness among farms as objectives while
131 these aspects are fundamental for the Sustainable Development Goals (SDG) set by the
132 United Nations (2019) and for the new business model also aligned with the Common
133 Agricultural Policy (CAP) Objectives.

134 Finally, few existing models to support the crop planning while considering
135 demand of crops take into consideration the uncertain nature of factors related to the
136 agri-food sector. In this case, Darby-Dowman et al. (2000) model the uncertainty of the
137 plants yield stochastically while. Ahumada et al. (2012) additionally
138 consider the stochastic nature of market prices. On their part, Najafabadi et al. (2019)
139 consider that the resources needed per crop are uncertain and modelled them by using
140 fuzzy sets. This paper models the uncertainty on the yield of plants, demand of crops,
141 and market and settlement prices by using fuzzy set theory since it is appropriate for
142 cases in which uncertainty is associated with vagueness, ambiguity, imprecision and/or
143 lack of information on a particular element of the problem at hand (Alemany et al.,
144 2015) which is our case.

145 Therefore, to the authors' knowledge, there is a gap in literature as regards
146 models for supporting the crop planning decisions in this new business model for
147 achieving a sustainable supply chain. The objective of the paper is to cover this gap by
148 developing a computerized tool based on a novel **Uncertain Multi-Objective**
149 **Centralized mathematical programming model for the Sustainable Crop Planning**
150 **Problem**, dubbed as UMO-SCPP hereunder. The UMO-SCPP model seeks to balance
151 the supply and demand of crops in an agri-food supply chain composed by farmers and
152 retailers without intermediaries and considers different characteristics of the business
153 model that to the best of authors' knowledge have not been previously modelled in
154 literature.

155 Main novelties of the proposed mathematical programming model are: i)
156 modelling of the new business model itself, ii) inclusion of collaboration among
157 stakeholders of the same SC stage, iii) anticipation of more operative decisions such as
158 harvest, transport, and sales decisions when defining the crop planning, iv) modelling of

159 the distribution of cargo into vehicles, v) consider the possibility of settling the
160 oversupply of crops in the same period of their harvest to guarantee the freshness of
161 crops and to reduce generated waste and supply chain losses, vi) modelling of multi-
162 objective approach considering the three aspects of sustainability by means not only
163 maximizing profits (economical objective) but also minimizing waste (environmental
164 objective,) and minimizing the economic unfairness among farmers for implementing
165 the collaborative approach (social objective), and vii) inclusion of inherent agri-food
166 supply chain uncertainty by fuzzy modelling of parameters related to the yield, demand
167 and prices of crops.

168 The UMO-SCPP model is validated with realistic data from an Argentinean case
169 study for two scenarios. Results show that it is possible to find solutions where the level
170 of unfairness among farmers and waste generated are improved by slightly decreasing
171 the total profit. Therefore, with this proposal we are contributing to increase the
172 sustainability of the agri-food supply chains in its three dimensions simultaneously.

173 The rest of the paper is aligned to the research methodology and is structured as
174 follows. The fuzzy multi-objective MILP model to address the problem under study and
175 the resolution methodology used to solve it are exposed in Section 2. Results are
176 analysed and discussed in section 3. Finally, conclusions and future research
177 lines are drawn in Section 4.

178 **2 Materials and Methods**

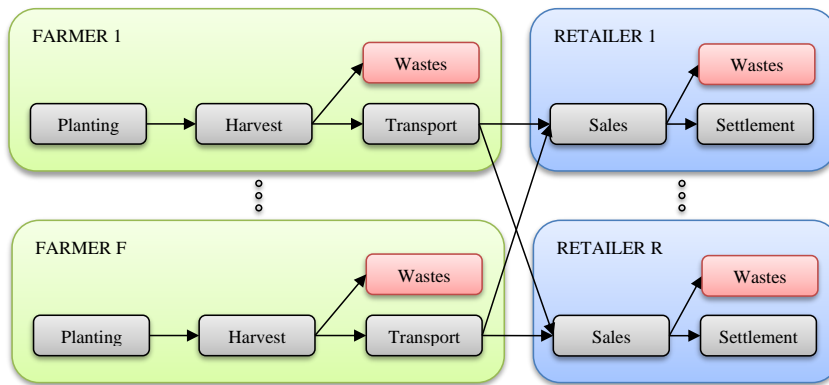
179 This section first explains the assumptions under which the crop planning problem is
180 solved for the new business model, followed by the fuzzy multi-objective mathematical
181 programming model to support crop planning decisions. Finally, the CPM-EES-U
182 model is transformed into an equivalent crisp model to facilitate its resolution.

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183 **2.1 Crop planning in the new business model**

184 The business model under study is characterized by the lack of intermediaries between
185 farms and retailers. Therefore, an agri-food supply chain composed by a set of farms
186 and retailers directly linked that produce and commercialize multiple crops with limited
187 shelf-life is considered (Figure 1).

188 Figure 1. Supply chain configuration and main activities.



189
190 Farmers are responsible for farming activities (planting, cultivation, and harvest)
191 and for the transport of crops to retailers, where crops are sold to end consumers. Each
192 farm disposes of one farming location with a limited planting area. Farmers define the
193 area to plant with each crop per period, considering that a minimum area needs to be
194 planted per selected crop and period due to technical reasons. The yield of plants
195 depends on the crop, and its planting and harvest date. All crop matured at plant needs
196 to be harvested in the same period. The transport of crops is made by trucks in a way
197 that a minimum percentage of the cargo quantity needs to be loaded to use one truck.

198 The business model also seeks to serve customers with very fresh products. To
199 do this, the considered supply chain transport and selling the products on the same
200 period of their harvest, being not allowed to store products from one period to the

201 following. So, crops harvested and not transported to retailers on the same period will
 202 be wasted in the farm level. On the other hand, all the crops that arrive to the retailer
 203 and are not sold in the same period will also be wasted. To reduce the wastes generated
 204 along the chain, this business model allows to settle a part of the oversupply of crops
 205 limited by a percentage of the demand with a reduced price. Finally, a minimum service
 206 level service is ensured for all crops in all retailers.

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207 **2.2 Fuzzy mathematical programming model formulation**

208 The nomenclature used to formulate the UMO-SCPP model is exposed in Table 1,
 209 where uncertain parameters are identified by the symbol $\tilde{\cdot}$. The uncertain parameters
 210 are modelled with Fuzzy Set Theory since it has proved their validity for the uncertainty
 211 associated with vagueness, imprecision, inexact statements, incomplete, lack of
 212 information and/or unobtainable information on a particular element (Mundi et al.,
 213 2016). This model considers that the sales and settlement prices, as well as the crop
 214 yields, and demands are uncertain parameters since their values cannot be known in
 215 advance.

216 Table 1. Nomenclature for the UMO-SCPP model.

Indexes	
c	Crops
p	Planting periods
t	Time periods
l	Farming locations
r	Retailers
Set of indexes	
P_c	Set of periods p in which crop c can be planted.
P_{cp}^t	Set of periods t in which crop c planted in period p can be harvested.
Parameters	
ap_l	Available area for planting in location l .
am_c	Minimum area to be planted with crop c when it is decided to plant it (technical reasons).
\tilde{y}_{cpt}	Yield of crop c planted at p and harvested at t .
\tilde{d}_{rct}	End consumers' demand of crop c at retailer r at period t .
\tilde{e}_{rct}	Excess of demand of crop c that can be sold at retailer r at a settlement price.
\tilde{p}_{rct}	Market price of crop c at retailer r at period t .
\tilde{op}_{rct}	Selling price of one kg of crop c at retailer r at period t .
\tilde{qp}_{rct}	Settlement price of one kg of crop c at retailer r at period t .
$b_{c_{rct}}$	Penalty cost for not meeting one kg of crop c demand at retailer r at period t .

p_c	Planting, cultivation and harvest cost for one plant of crop c .
t_{lrc}	Cost of transporting one kg of crop c from location l to retailer r .
sl_c	Minimum service level for each crop c .
cc	Fix cost of using one truck.
cap	Capacity of one truck in kilograms.
mc	Minimum percentage of the truck capacity that should be filled to be used.
Variables	
A_{lcp}	Area planted in location l with crop c at planting period p .
H_{lct}	Quantity of crop c harvested at location l in period t .
WL_{lct}	Quantity of crop c wasted at location l at period t after its harvest.
T_{lrct}	Quantity of crop c transported from location l to retailer r in period t .
N_{lrt}	Number of trucks required to transport crops from location l to retailer r in period t .
W_{rct}	Quantity of crop c wasted at retailer r at period t .
S_{rct}	Quantity of crop c sold at retailer r at period t .
B_{rct}	Unmet demand of crop c at retailer r at period t .
G_{rct}	Quantity of crop c settled at retailer r at period t .
D_l	Difference between the region and location l profit per area (absolute value).
Y_{lcp}	Binary variable with value equal to one when location l plant crop c at period p , and zero otherwise.
Y_{rct}	Binary variable that takes value equal to one when demand of crop c at period t and retailer r is higher than supply, and zero otherwise.

217 The triple bottom line is modelled with three objectives that combined through
218 the weighted sum method (Marler and Arora, 2010) conform a single objective function
219 (1). The objectives are scaled by dividing their values between the maximum value that
220 they can acquire. These maximum values are obtained by executing the model
221 maximizing only one objective (Z_{EC} , Z_{ENV} , or Z_{SOC}).

$$Max Z = w_{EC} \cdot \frac{Z_{EC}}{Z_{EC,max}} - w_{ENV} \cdot \frac{Z_{ENV}}{Z_{ENV,max}} - w_{SOC} \cdot \frac{Z_{SOC}}{Z_{SOC,max}} \quad (1)$$

222 The economic objective (Z_{EC}) maximizes the supply chain profits (2). The first
223 term represents the sales obtained by demanded crops and settled crops. The rest of
224 terms are related to the costs for planting, cultivation and harvest, transport of crops and
225 penalizations for unmet demand. Since market and settlement prices for each crop,
226 retailer and period are not known in advance to the crop planning decision and fluctuate
227 as a consequence of the balance between supply and demand among other factors, these
228 parameters are considered uncertain in this model.

$$Z_{EC} = \sum_r \sum_c \sum_t (\bar{s}p_{rct} \cdot S_{rct} + \bar{g}p_{rct} \cdot G_{rct} - bc_{rc} \cdot B_{rct}) - \sum_l \sum_c \sum_{p \in P_c} p c_c \cdot A_{lcp} \\ - \sum_l \sum_r \sum_c \sum_t t c_{lrc} \cdot T_{lrct} - \sum_l \sum_r \sum_t cc \cdot N_{lrt} \quad (2)$$

229 The environmental objective minimizes wastes along the chain (3). Wastes can
 230 be generated at the farming location by crops not distributed to the following stages of
 231 the supply chains, and at retailers when there is an oversupply of crops that cannot be
 232 finally be settled.

$$Z_{ENV} = \sum_c \sum_t \left(\sum_r W_{rct} + \sum_l WL_{lct} \right) \quad (3)$$

233 The social objective minimizes the economic unfairness among farmers (4),
 234 calculated as the absolute difference between the overall profit per area for farming
 235 locations and the profit per area per each farming location. This objective is one of the
 236 main novelties of this model. The non-linearity of this objective is solved by replacing it
 237 with (5-7) where PR (8) and PL_l (9) are the overall profit for farming locations and the
 238 profit per each farming location l , respectively. Profits at the farm level are calculated as
 239 the difference between the sale of crops to retailers and costs related to the planting and
 240 transport of crops. The selling price for each crop at this level is also modelled as an
 241 uncertain parameter as it cannot be known in advance given its dependence to several
 242 factors such as the market prices.

$$Z_{SOC} = \sum_l \left| \frac{PL_l}{ap_l} - \frac{PR}{\sum_l ap_l} \right| \quad (4)$$

$$Z_{SOC} = \sum_l D_l \quad (5)$$

$$D_l \geq \frac{PL_l}{ap_l} - \frac{PR}{\sum_l ap_l} \quad \forall l \quad (6)$$

$$D_l \geq \frac{PR}{\sum_l ap_l} - \frac{PL_l}{ap_l} \quad \forall l \quad (7)$$

$$PR = \sum_t \left(\sum_r \sum_c \sum_t (\overline{op}_{rct} - tc_{lrc}) \cdot T_{lrct} - \sum_c \sum_{p \in P_c} pc_c \cdot A_{lcp} - \sum_r \sum_t cc \cdot N_{lrt} \right) \quad (8)$$

$$PL_l = \sum_r \sum_c \sum_t (\overline{op}_{rct} - tc_{lrc}) \cdot T_{lrct} - \sum_c \sum_{p \in P_c} pc_c \cdot A_{lcp} - \sum_r \sum_t cc \cdot N_{lrt} \quad \forall l \quad (9)$$

243 The UMO-SCPP model is subjected to the following constraints. The area
 244 allocated to each crop in all periods cannot exceed the total area of each farm (10).

$$\sum_c \sum_{p \in P_c} A_{lcp} \leq ap_l \quad \forall l \quad (10)$$

245 In case a crop is planted, the minimum planted area is limited due to technical
 246 reasons (11). In addition, no more area than the corresponding to the farmer can be
 247 planted with the same crop.

$$amin_c \cdot YP_{lcp} \leq A_{lcp} \leq ap_l \cdot YP_{lcp} \quad \forall l, c, p \in P_c \quad (11)$$

248 Mature crops at plants are necessarily harvested (12) and transported to markets
 249 or wasted in this same period due to the limited shelf-life of crops (13). The yield of
 250 plants is considered as an uncertain parameter in this model since it is dependent of
 251 uncontrollable factors such as the weather, soil properties among others.

$$\sum_{p \in P_c} \tilde{y}_{cpt} \cdot A_{lcp} = H_{lct} \quad \forall l, c, t \quad (12)$$

$$H_{lct} = WL_{lct} + \sum_r T_{lrct} \quad \forall l, c, t \quad (13)$$

252 To correctly calculate the wastes produced at the farm level it is necessary to
 253 take into account the limited availability of transport, aspect that have not been
 254 previously modelled in other models. Therefore, a minimum quantity of crops needs to
 255 be transported in order to use one truck, and the transported quantity cannot exceed the
 256 capacity of trucks (14).

$$cap \cdot mc \cdot N_{lt} \leq \sum_c T_{lct} \leq cap \cdot N_{lt} \quad \forall l, t \quad (14)$$

257 All crops transported to retailers need to be sold or wasted in the same period of
 258 their transport since the business model under study does not allow to store perishable
 259 crops from one period to the following. With this, costs related to the workforce and
 260 facilities needed to the cold storage of perishable crops at retailers is eliminated. In
 261 addition, in order to reduce the quantity of wastes generated at markets, it is allowed to

262 settle crops in cases in which supply excess demand, which is a novelty of this model.
 263 Therefore, crops that arrive to markets are necessarily sold, settled, or wasted in the
 264 same period due to the limited shelf-life of crops and the business model implemented
 265 (15).

$$\sum_t T_{rct} = S_{rct} + G_{rct} + W_{rct} \quad \forall r, c, t \quad (15)$$

266 A minimum service level needs to be guaranteed when meeting demand (16).
 267 This ensures that a part of the demand fixed by the decision makers will be necessarily
 268 met for each crop in each retailer. The demand for each crop is also modelled as an
 269 uncertain parameter since it cannot be known in advance to the period of sales.

$$\sum_t S_{rct} \geq \sum_t sl_c \cdot \tilde{d}_{rct} \quad \forall r, c \quad (16)$$

270 In addition, in cases in which demand is higher than the supply, a part of the
 271 demand can be lost. So, the sum of sales and unmet demand for each crop, period and
 272 retailer should be equal to the demand of such crop. Thus, the unmet demand can only
 273 be produced in cases in which demand excess supply (18).

$$S_{rct} + B_{rct} = \tilde{d}_{rct} \quad \forall r, c, t \quad (17)$$

$$B_{rct} \leq \tilde{d}_{rct} \cdot Y_{rct} \quad \forall r, c, t \quad (18)$$

274 On the other hand, the demand for settled crops is limited by a percentage of the
 275 demand (19). The settlement of crops is only allowed in this business model in cases in
 276 which there is an oversupply of crops.

$$G_{rct} \leq \tilde{e}_{rct} \cdot \tilde{d}_{rct} \cdot Y_{rct} \quad \forall r, c, t \quad (19)$$

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

$$\begin{array}{ll} A_{lcp}, H_{lct}, WL_{lct}, T_{lct}, W_{ct}, S_{ct}, B_{ct}, G_{ct}, D_l, PR, PL_l & CONTINUOUS, \\ N_{lt} & INTEGER \\ YP_{lcp} & BINARY \end{array} \quad (20)$$

278 **2.3 Solution Method**

279 The methodology proposed by Jiménez et al. (2007) to transform a fuzzy model into an
 280 equivalent crisp model is used in this paper. We refer readers to the original paper
 281 (Jiménez et al., 2007) for more information about this method. In this paper, it is
 282 assumed that fuzzy parameters (\tilde{a}) are characterized by triangular membership functions
 283 ($\tilde{a} = (a^1, a^2, a^3)$) that represent the most pessimistic, possible and optimistic values for
 284 the uncertain parameters (Mula et al. 2010), what is in concordance with the problem
 285 under study. The auxiliary crisp model is formulated as follows where parameter α
 286 represents the degree of feasibility for each solution and ranges between 0 and 1, being
 287 1 the value related to the highest degree of feasibility of a solution:

$$Max Z = w_{EC} \cdot \frac{Z_{EC}}{Z_{ECmax}} - w_{ENV} \cdot \frac{Z_{ENV}}{Z_{ENVmax}} - w_{SOC} \cdot \frac{Z_{SOC}}{Z_{SOCmax}} \quad (1)$$

288 Subject to:

(3)-(7), (10), (11), (13)-(15), (20)

$$Z_{EC} = \sum_r \sum_c \sum_t \left(\frac{sp_{rct}^1 + 2 \cdot sp_{rct}^2 + sp_{rct}^3}{4} \cdot S_{rct} + \frac{gp_{rct}^1 + 2 \cdot gp_{rct}^2 + gp_{rct}^3}{4} \cdot G_{rct} \right. \\ \left. - bc_{rc} \cdot B_{rct} \right) - \sum_l \sum_c \sum_p pc_c \cdot A_{lcp} - \sum_l \sum_r \sum_c \sum_t tc_{lrc} \cdot T_{lrc} \\ - \sum_l \sum_r \sum_t cc \cdot N_{lrc} \quad (21)$$

$$PR = \sum_l \left(\sum_r \sum_c \sum_t \left(\frac{op_{rct}^1 + op_{rct}^2 + op_{rct}^2 + op_{rct}^3}{4} - tc_{lrc} \right) \cdot T_{lrc} - \sum_c \sum_p pc_c \cdot A_{lcp} \right. \\ \left. - \sum_r \sum_t cc \cdot N_{lrc} \right) \quad (22)$$

$$PL_l = \sum_r \sum_c \sum_t \left(\frac{op_{rct}^1 + op_{rct}^2 + op_{rct}^2 + op_{rct}^3}{4} - tc_{lrc} \right) \cdot T_{lrc} - \sum_c \sum_p pc_c \cdot A_{lcp} \\ - \sum_r \sum_t cc \cdot N_{lrc} \quad \forall l \quad (23)$$

$$\sum_{p \in P_c} \left[\left(1 - \frac{\alpha}{2}\right) \cdot \left(\frac{y_{cpt}^1 + y_{cpt}^2}{2}\right) + \left(\frac{\alpha}{2}\right) \cdot \left(\frac{y_{cpt}^2 + y_{cpt}^3}{2}\right) \right] \cdot A_{lcp} - H_{lct} \leq 0 \quad \forall l, c, t \quad (24)$$

$$\sum_{p \in P_c} \left[\left(1 - \frac{\alpha}{2}\right) \cdot \left(\frac{y_{cpt}^2 + y_{cpt}^3}{2}\right) + \left(\frac{\alpha}{2}\right) \cdot \left(\frac{y_{cpt}^1 + y_{cpt}^2}{2}\right) \right] \cdot A_{lcp} - H_{lct} \geq 0 \quad \forall l, c, t \quad (25)$$

$$\sum_t S_{rct} \geq \sum_t \left[\alpha \cdot \frac{d_{rct}^2 + d_{rct}^3}{2} + (1 - \alpha) \cdot \frac{d_{rct}^1 + d_{rct}^2}{2} \right] \cdot sl_c \quad \forall r, c \quad (26)$$

$$S_{rct} + B_{rct} \leq \left(\frac{\alpha}{2}\right) \cdot \left(\frac{d_{rct}^1 + d_{rct}^2}{2}\right) + \left(1 - \frac{\alpha}{2}\right) \cdot \left(\frac{d_{rct}^2 + d_{rct}^3}{2}\right) \quad \forall r, c, t \quad (27)$$

$$S_{rct} + B_{rct} \geq \left(\frac{\alpha}{2}\right) \cdot \left(\frac{d_{rct}^2 + d_{rct}^3}{2}\right) + \left(1 - \frac{\alpha}{2}\right) \cdot \left(\frac{d_{rct}^1 + d_{rct}^2}{2}\right) \quad \forall r, c, t \quad (28)$$

$$B_{rct} \leq \left[\alpha \cdot \frac{d_{rct}^1 + d_{rct}^2}{2} + (1 - \alpha) \cdot \frac{d_{rct}^2 + d_{rct}^3}{2} \right] \cdot Y_{rct} \quad \forall r, c, t \quad (29)$$

$$G_{rct} \leq \left[\alpha \cdot \frac{e_{rct}^1 + e_{rct}^2}{2} + (1 - \alpha) \cdot \frac{e_{rct}^2 + e_{rct}^3}{2} \right] \cdot \left[\alpha \cdot \frac{d_{rct}^1 + d_{rct}^2}{2} + (1 - \alpha) \cdot \frac{d_{rct}^2 + d_{rct}^3}{2} \right] \cdot Y_{rct} \quad \forall r, c, t \quad (30)$$

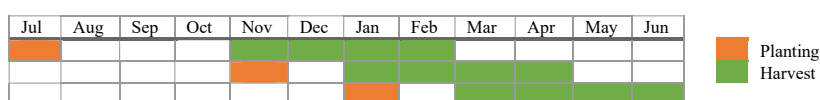
289 3 Computational experiments: Application to the Argentinean case study

290 The UMO-SCPP model was implemented in MPL® 5.0.8 and solved by using the
 291 solver Gurobi™ 8.1.1 in a computer with an Intel® Xeon® CPU E5-1620 v2(C)
 292 @3.70GHz processor, with an installed capacity of 35GB and a 64-bits operating
 293 system. Microsoft Access Database was used to store input data and obtained results.

294 The UMO-SCPP model is solved for an Argentinean case study in which the
 295 determination of the final sales price for agricultural products depends on diverse
 296 factors such as the production, commercialization and consumption structure, the power
 297 of the actors implied in the price fixing, and the balance between supply and demand.
 298 Thus, the Argentinean government is implementing national policies prioritizing
 299 familiar farming, promoting direct commercialization channels, and boosting sales at
 300 major markets so that supply and demand at commercialization link have a greater level
 301 of concentration enabling farmers to not only be price takers.

302 In the considered case study, a set of farms located in the region of La Plata
 303 define the weekly crop planning for three varieties of tomato for the next year. All
 304 varieties share the same planting/harvest calendar (Figure 2). Demand and prices are
 305 extracted from the Buenos Aires Central Market webpage. The rest of data is gathered
 306 from interviews with Argentinean farming experts from the Universidad de La Plata.
 307 All data can be found at <https://cigip.webs.upv.es/docs/CropPlanningData.ods>. In case
 308 of fuzzy parameters, obtained data is used as the most possible values for their
 309 membership functions while the lower and upper bounds are obtained by varying these
 310 central values by 10%.

311 Figure 2. Planting/Harvest calendar.



313 The weights assigned to each objective differentiate between their importance
 314 (Song and Kang, 2016). When defining the weights assigned to the objectives that
 315 compose the global objective function, decision makers hardly know their preferences
 316 and how to quantify them (Mavrotas, 2009). The Analytic Hierarchy Process (AHP)
 317 (Saaty, 1990) facilitates this task by obtaining the relative importance of elements, in
 318 this case the objectives, from a subjective comparison of their importance. For that, a
 319 paired comparison of the objectives is done by using the scale proposed by Saaty (1990)
 320 that gives higher values to most relevant elements. The weight to be assigned to each
 321 objective is then calculated by dividing the sum of values assigned to each objective by
 322 the sum of all values of the comparison matrix. The comparison matrix and the obtained
 323 weight distribution for this case study are shown in Table 4.

324 Table 4. Pairwise comparison matrix

	Z_{EC}	Z_{ENV}	Z_{SOC}	w_f
Z_{EC}	1	5	5	0.66
Z_{ENV}	1/5	1	1/3	0.09
Z_{SOC}	1/5	3	1	0.25

325 The UMO-SCPP model is solved for 11 α -cuts representing the degree of
 326 feasibility of the solution and for the weights' distribution extracted from the AHP
 327 (TBL scenario). The model is also solved by assigning all the weight to the economic
 328 objective (economic scenario) to extract managerial insights from the comparison of
 329 results. Solutions obtained for the triple bottom line indicators (supply chain profits,
 330 wastes and unfairness among farms) by both scenarios are shown in Figures 3 to 5
 331 where the blue line correspond to the economic scenario where all weight is assigned to
 332 the supply chain profit and the orange line correspond to the TBL scenario that assigns
 333 weights to the three objectives of the global objective function.

334 Figure 3. Results – Supply chain profits.



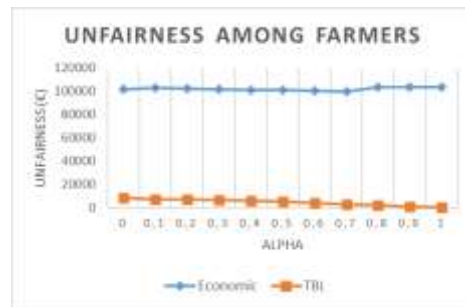
335

336 Figure 4. Results – Wastes.



337

338 Figure 5. Results – Unfairness among farmers.



339

340 From results obtained for the economic scenario, it is extracted that it obtains the
341 best profits for the entire supply chain in all α -cuts. However, wastes associated with
342 these profits are high and make up over 52% of the total harvest. In addition, the total
343 profits obtained at the agricultural level are only distributed among the 30% of the
344 farmers so that some farmers obtain losses (up to -22000 €/ha) while others obtain great
345 profits (up to 25000 €/ha). This generates a great perception of unfairness among
346 farmers, preventing them from collaborating and abiding the planning obtained with the
347 centralized model.

348 On the other hand, the TBL scenario that represents the new business model
349 arising in the agri-food sector obtains lower profits to the economic scenario. However,
350 this scenario shows improvements in terms of wastes and economic unfairness among
351 farmers. In the case of wastes, these can account for 30% of the total harvest, which
352 despite representing a high percentage shows a significant improvement with respect to
353 the economic scenario. In this case, the profits at the agricultural level are distributed
354 among all farmers, obtaining a minimum of 55 €/ha and a maximum of 2400 €/ha.
355 Therefore, the feeling of fairness among farms is greatly benefited in the TBL scenario
356 with respect to the economic scenario, making farmers more participatory and willing to
357 implement the obtained planning.

358 Therefore, it is extracted from the comparison between the results obtained by
359 both scenarios that the environmental and social aspects of sustainability can be highly
360 improved in exchange for a slight decrease in the economic results. For example, by
361 considering the proposed multi-objective approach, reducing the obtained profits at the
362 economic scenario in an 8 to 9% leads to the reduction of the quantity of crops wasted (-
363 47% in average with regard to the economic scenario) and of the economic unfairness
364 among farmers (-95% in average with regard the economic scenario). In addition, the
365 reduction on the economic unfairness among farmers encourages them to comply with
366 decisions made in a centralized way, avoiding the unwillingness to collaborate that is
367 usually related to the centralization of the decision-making process.

368 The values obtained for the models' objectives per α -cut get worse for both
369 scenarios as the degree of feasibility (α) of the solution increases. This is because the
370 constraints with fuzzy parameters are more flexible when the feasibility degree decreases.
371 Therefore, a balance between the satisfaction of the value obtained for each objective and
372 the degree of feasibility of the solution should be made by decision makers in order to select
373 the solution to be finally implemented in the real agri-food supply chain (Esteso et al.,
374 2018b).

375 The solved model counted with 6,724 constraints and 6,181 variables from
376 which 5,415 were continuous, 520 were integer and 246 were binary variables. Optimal
377 solutions were found for all α scenarios with an average resolution time of 1.27 seconds.

378 **4 Conclusions**

379 A multi-objective model called UMO-SCPP to centrally define the crop planning for an
380 agri-food supply chain under uncertain context is designed for a new business model.

381 The UMO-SCPP model optimizes three objectives aligned to the triple bottom line. A

382 single objective is constructed by applying the weighted sum method and the weights
383 distribution is defined with the AHP (TBL scenario) or by assigning all weight to
384 economic objective (economic scenario).

385 After analysing mathematical programming models to support crop planning
386 while considering the crops demand, it was found that main novelties of this proposal
387 are: i) modelling of a new business model, ii) collaboration among stakeholders of the
388 same SC stage, iii) joint modelling of crop planning, harvest, transport and sales
389 decisions, iv) modelling of the distribution of cargo into vehicles, v) settlement of
390 overproduction to reduce wastes, supply chain losses and to ensure the freshness of sold
391 crops, vi) multi-objective approach considering the three aspects of sustainability, vii)
392 minimization of wastes as an environmental objective, viii) minimization of economic
393 unfairness among farmers as a social objective, and ix) fuzzy modelling of parameters
394 related to the yield, demand and prices of crops.

395 Results show that optimizing environmental and social aspects of sustainability
396 leads to crop planning with economic results similar to the obtained by only optimizing
397 the economic objective. In addition, such solutions highly reduce the quantity of wastes
398 along the supply chain, and the economic unfairness among the actors of the agri-food
399 supply chain. Thus, the proposed model and its results contribute to the following
400 Sustainable Development Goals (SDGs) from the United Nations: 2) Zero Hunger, 10)
401 Reduced Inequalities, 12) Responsible consumption and production, and 17)
402 Partnerships for the goals from the United Nations.

403 The multi-objective approach considered in this paper based on the weighted
404 sum method has some limitations for the implementation of results in the real agri-food
405 supply chain. This results from the fact that the distribution of weights to objectives
406 depends on the subjectivity of decision makers. In addition, the obtained solution can

407 only be the optimum for the defined weights distribution. To solve this, the UMO-SCPP
408 model could be solved in the future with the ϵ -constraint method to obtain a set of non-
409 dominated solutions not influenced by the subjectivity of decision makers when
410 defining the distribution of weights among objectives. In this case, a method to choose
411 the most satisfactory solution for the supply chain should be defined.

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