Small-Producer Selection and Order Allocation in the Agri-Food Supply Chain

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***Abstract*—Producer diversification and order allocation are problems in the operational research field that require decision-making skills from the side retailers so that they can choose from who and when to place orders to meet their demand. These tasks are especially challenging in the agricultural field since orders need to be placed months in advance for some products to take into account the time required for planting and farming the produce. This work presents an exploratory model that tackles the challenge of farmer selection and order allocation. We develop a linear program that minimizes the demand cost while considering quantity-dependent pricing and a variety of constraints that agricultural retailers face.**

***Index Terms*—Supply planning, Order allocation, Supplier selection, Dynamic demand, Flexibility, Multiple sourcing**

I. INTRODUCTION

Supplier selection and order allocation problems are well-known multi-criterion problems that aim to find the best set of suppliers to purchase products from, along with the best schedules to place the orders and their quantities. These decisions are all made depending on a variety of characteristics that the suppliers have and a set of demands that the clients have. Research shows that supplier selection and order allocation problems are interdependent and that considering both problems when decision-making will result in better solutions [1]. Therefore, in this work, we tackle both of these problems while focusing on the agricultural field. In this formulation, the suppliers are small-scale farmers, or what we will refer to as smallholders, and the retailer is "Le Mas des Agriculteurs", which is an association that works as a retailer between the small-scale farmers of the Gard department in France and possible buyers. In this scenario, Le Mas des Agriculteur will need to place monthly orders at the smallholders to meet the client's demands while considering the lead time it takes farmers to plant and cultivate their produce. To do so, this association employs contract farming, which places the orders months in advance to allow the farmers time to plan and meet the order. This process is represented in Figure 1. Therefore, "Le Mas des Agriculteurs" has to start planning the orders early while considering each of the smallholder's varying prices, production capacities, holding costs, and storage capacities while attempting to minimize the purchasing cost of the demands. Additionally, the model needs to consider that most smallholders have quantity-dependent pricing, whereby an increase in the quantity purchased will decrease the product's unit price. Considering all these variables, the supplier selection and order allocation problems become too complex to solve manually.

In this work, we propose a linear program (LP) that tackles the challenge of small-producer selection and order allocation based on data from 'Le Mas des Agriculteurs". The LP is tasked with choosing which quantities of a given product should "Le Mas des Agriculteurs" buy from which producers and at which period. The model takes into consideration the following parameters:

- Dynamic demand: the clients' demand will change across the year;
- Dynamic production capacity: Each smallholder has their own production capacity, which will vary across the year and will go through some low production phases and high production phases;
- Dynamic unit holding cost: Each smallholder has their own holding cost, which will vary across the year. During periods of high temperatures, the smallholders might increase their holding costs to account for the increase in energy consumption;
- Dynamic storage capacity: Each smallholder has their own inventory, which he manages. Its capacity to store the products ordered by "Le Mas des Agriculteurs" might change across the year depending on which other products he plans to store in his inventory;
- Ordering cost: Each smallholder has their own ordering cost;
- Unit price: Each smallholder has their own unit price for the produce;
- Quantity-dependent pricing: Some smallholders offer a discount on the unit price of the product when large quantities are ordered.

The rest of this work is divided as follows: we review some of the methods developed for supplier selection in Section II, we describe the proposed approach in Section III, we showcase a numerical example in Section IV and analyze the impact of different parameters in Section V, to finally conclude in Section VI.

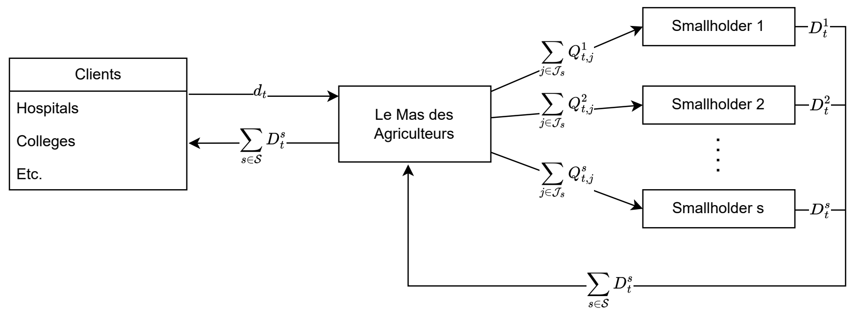

Fig. 1. Relationship between clients, “Le Mas des Agriculteurs” and smallholders.

II. Literature Review

The supplier selection problem and order allocation are crucial challenges in operational research, whereby different variations exist. These variables include the time scale, whereby it could be continuous or discrete if the model should plan for multiple items (multi-items) or a single one (single item). There can also be a variety of relevant costs (transportation, inventory holding cost, lost sales, etc.) and a variety of resource constraints [2]. Additionally, the end goal might be to choose a single supplier to buy from (mono-sourcing) or multiple ones (multi-sourcing) [3]. In this review, we focus on some papers that tackled the single-item, multi-sourcing variant of the problem. There have been many works that tackled this variation of the problem. Some used deterministic approaches, while others employed stochastic ones. As an example of deterministic models, the works in [4], [5] developed a variety of dynamic programming techniques. Other works employed linear programming, such as in [6] where a two-stage fuzzy supplier selection and order allocation model in a circular supply chain is presented. The model took into consideration the possibility of recycling and re-manufacturing. Their work employed a mixed integer linear programming model, which not only aimed to minimize the cost but also to minimize the environmental impact and increase job opportunities. The work in [7] focused on sustainable supplier selection and order allocation and used the ϵ-constraint method to combine different costs of the order and its environmental impact into a single objective function. The authors then used the Benders decomposition algorithm to tackle this problem. In [8], the authors aimed to find purchasing plans that minimize purchasing and inventory costs while taking into consideration lead time uncertainty. To do so, the authors developed a robust model based on the exact row and column generation algorithm. The authors also put forward multiple heuristics aimed at tackling the problem in the case of large instances. In [9], the authors studied the supplier selection and order allocation problems for a two-echelon supply network. The authors used mixed integer non-linear programming and the Taguchi Method of Tolerance Design to handle uncertainties and ensure robust decision-making. In [10], the authors focused on multi-period multi-sourcing supply planning with stochastic lead-times, quantity-dependent pricing, and delivery flexibility costs. They developed a linear programming model that takes into consideration the holding and backlog costs and finite capacities of suppliers,

On the other hand, stochastic models and robust optimization were also used for these problems. For example, the work of [11] which focused on managing the available resources and inventory using a genetic algorithm under stochastic lead times and demand. The work in [12] proposed a hybrid ant colony optimizer-genetic algorithm and used the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method to evaluate their suppliers.

The literature shows the multitude of methods developed to tackle these problems. We build over this previous work by modeling a linear program for the case study of “Le Mas des Agriculteurs” and focusing on the single-item, multiple suppliers, dynamic-lot sizing variant.

III. Problem Formulation

To tackle the problems of supplier selection and order allocation, we propose an LP tailored to the needs of “Le Mas des Agriculteurs”. The model follows a multi-sourcing policy with quantity-dependent pricing. In this formulation, “Le Mas des Agriculteurs” has a list of internal smallholders that they would like to employ. These smallholders have a dynamic production capacity and quantity-dependent pricing. These smallholders can stock their supplemental produce to sell later, but each has a dynamic holding cost that Le Mas des Agriculteur would need to reimburse. One thing to note, however, is that this model does not support backlogging, as most of the clients are hospitals and colleges that need to meet their cafeterias’ needs. So if the internal smallholders cannot meet the client’s demand, “Le Mas des Agriculteurs” would need to buy the product from an external producer, usually at a higher price.

The proposed linear programming model is inspired by the work of [10], and uses the notation described in Table I.

The model is the following:

$$\text{TC}: \min \sum_{t \in \mathcal{T}} \sum_{s \in \mathcal{S}} \Big(h_t^s I_t^s + \sum_{j \in \mathcal{J}_s} (p_j^s . Q_{t,j}^s + o^s Y_{t,j}^s) \Big) \qquad (1)$$

Subject to constraints:

$$I_t^s \geq \sum_{\tau=1}^{t} \sum_{j \in \mathcal{J}_s} Q_{t,j}^s - \sum_{\tau=1}^{t} D_\tau^s \quad \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \qquad (2)$$

TABLE I
NOTATIONS.

Parameters	
$\mathcal{S}$	set of smallholders
$\mathcal{T}$	number of time buckets
s	index of smallholders, $s \in \mathcal{S}$
t	index of the period
$\mathcal{J}_s$	ordered set of indices of quantity intervals defining supplier's pricing policy
$[l_{sj}, u_{sj}]$	lower and upper limits of the j-th quantity interval of smallholder s pricing policy
p^s_j	unit selling price of the j-th quantity interval of smallholder s pricing policy
c^s_t	capacity limit of smallholder s at period t
d_t	monthly fixed demand
h^s_t	unit inventory holding cost of smallholder s at period t
o^s	fixed ordering cost of smallholder s
i^s_t	storage capacity of smallholder s at period t
Variables	
D^s_t	**integer decision variable** that gives the delivered quantity from supplier s at the end of period t
I^s_t	inventory level of supplier s at the end of period t
$Q^s_{t,j}$	**integer decision variable** that gives the total quantity to order from smallholder s within the j-th interval of its pricing policy at period t
$Y^s_{t,j}$	**binary decision variable** indicating if the total ordered quantity from smallholder s at period t is within the j-th interval of its pricing policy

$$\sum_{s\in\mathcal{S}} D^s_t \geq d_t \quad \forall t \in \mathcal{T} \tag{3}$$

$$I^s_t \leq i^s_t \quad \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \tag{4}$$

$$\sum_{j\in\mathcal{J}_s} Q^s_{t,j} \leq c^s_t \quad \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \tag{5}$$

$$l_{sj} Y^s_{t,j} - Q^s_{t,j} \leq 0 \quad \forall s \in \mathcal{S}, \forall t \in \mathcal{T}, \forall j \in \mathcal{J}_s \tag{6}$$

$$Q^s_{t,j} - u_{sj} Y^s_{t,j} \leq 0 \quad \forall s \in \mathcal{S}, \forall t \in \mathcal{T}, \forall j \in \mathcal{J}_s \tag{7}$$

$$I^s_t \geq 0 \quad \forall s \in \mathcal{S}_{\setminus|\mathcal{S}|}, \forall t \in \mathcal{T} \tag{8}$$

$$I^{|\mathcal{S}|}_t = 0 \quad \forall t \in \mathcal{T} \tag{9}$$

$$\sum_{j\in\mathcal{J}_s} Y^s_{t,j} \leq 1 \quad \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \tag{10}$$

$$Y^s_{t,j} \in \{0,1\} \quad \forall s \in \mathcal{S}, \forall j \in \mathcal{J}_s, \forall t \in \mathcal{T} \tag{11}$$

$$Q^s_{t,j}, D^s_t \geq 0 \quad \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \tag{12}$$

The objective function (1) of the model attempts to minimize the purchasing and storage costs of the product and the ordering costs. Constraints (2) give the inventory level at each period $t \in \mathcal{T}$. Constraints (3) ensure that for every period, the total quantity delivered by the smallholders meets the demand of the clients. Constraints (4) ensure that the storage capacity of every smallholder is respected across all periods. Constraints (5) ensure that the production capacities of every smallholder during all the periods are respected. Constraints (6-7) ensure that the $Y^s_{t,j}$ values are set to one when the model suggests buying quantities from its corresponding $Q^s_{t,j}$. Constraints (8) ensure that the inventory level stays positive since backlogging is not tolerated, whereas expressions (9) prevent the model from taking into consideration the inventory level of the external smallholder to match this real-life constraint. Constraints (10) ensure that the quantities ordered from a given smallholder at a given time period (if any) belong to a single pricing bucket. Constraints (11) reinforce that $Y^s_{t,j}$ are binary values, and Constraints (12) ensures that the $Q^s_{t,j}$ and D^s_t are positive numbers as they refer to the quality ordered and delivered, these values cannot be negative.

IV. NUMERICAL EXAMPLE

The capacitated single-item lot sizing problem is NP-hard, in general, [13]. It is even NP-hard for very special cases such as C/G/Z/NI where the setup cost is constant, the holding cost is time-independent, the production cost is zero, and the capacity is non-increasing [14]. This problem can arise from the relaxation of our problem (with constant setup and purchasing costs and time-independent holding costs and capacity), which is represented as C/G/C/G. Therefore, our problem is NP-hard, even without considering the multi-sourcing policy and the storage capacity constraints.

We test the performance of our proposed model on an instance inspired by the scenarios discussed with "Le Mas des Agriculteurs". In this example, there is a phase where the production of the internal smallholders is abundant, followed by a phase where their production is insufficient. The model needs to decide whether it is more beneficial to order an excessive amount of product during the prosperous phase and stock the surplus for later or order from the external supplier. In this scenario, we consider potato production as it is a staple vegetable in the plates served at the cafeterias. The considered demand is shown in Table II. To avoid overcomplicating the example, we consider that there are three internal suppliers of potatoes for "Le Mas des Agriculteurs", along with one external supplier.

TABLE II
THE DEMAND (IN TONNES) ACROSS ONE YEAR.

t	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
d_t	15	15	20	25	27	30	35	30	25	20	22	15

The production capacity c^s_t of the smallholders for every time period is described in Table III. In this table, S_4 is the external supplier. They have an infinite production capacity throughout the entire year, but they do not have storage capacity.

Table IV shows the quantity-dependent pricing of these smallholders. The prices of S_4 are significantly higher than the internal smallholders to match the real-life case.

Table V shows the available inventory space for all the smallholders, and Table VI shows their holding cost.

To solve this instance of the problem, the algorithm was implemented using Python language with the CPLEX solver. The test was carried out with a 12th Gen Intel(R) Core(TM) i9-12900H processor and 64 GB of RAM. The exact solution is found in a short computational time that does not exceed 0.5 seconds.

Table VII shows that the model took advantage of the periods of prosperity by ordering excessive quantities of the product during the periods 4 and 6 where the ordered quantities were

TABLE III
THE PRODUCTION CAPACITY (IN TONNES/PERIOD) AND ORDERING COST (IN €) OF THE SMALLHOLDERS.

Capacity c_t^s		Period t												Ordering cost o^s
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	
Smallholder s	**1**	5	15	20	20	15	10	10	5	0	0	0	0	10
	2	2	15	25	30	35	30	20	15	5	0	0	0	23
	3	10	30	30	35	45	30	25	20	15	10	10	0	15
	4	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	45

TABLE IV
QUANTITY-DEPENDENT PRICING OF THE SMALLHOLDERS (IN €/ TONNE).

$[l_{1j}, u_{1j}]$	$[0, 5]$	$[6, 10]$	$[11, 15]$	$[16, 20]$
p_j^1	1200	1100	950	850
$[l_{2j}, u_{2j}]$	$[0, 7]$	$[8, 15]$	$[16, 30]$	
p_j^2	1400	1300	1050	
$[l_{3j}, u_{3j}]$	$[0, 10]$	$[11, 15]$	$[16, 25]$	$[26, 35]$
p_j^3	1500	1350	1200	1100
$[l_{4j}, u_{4j}]$	$[0, 10]$	$[11, 20]$	$[21, 30]$	$[31, \infty[$
p_j^4	5500	5100	4600	4000

bigger than the demand. This excess was stored in inventory until the production capacity could not meet the demand, and they were used to assist Le Mas des Agriculteur in fulfilling the demand. Then, once the inventory levels started to diminish, the model turned to the external supplier and placed orders there.

To further understand the behavior of the model and the impact of the parameters, we perform a variable analysis in the following section. This would allow the study of the behavior of the model and would aid in increasing the purchasing from the internal smallholders.

V. MANAGERIAL INSIGHTS

In this section, we fluctuate the variables of the smallholders' fractions of their value in order to study how the model would behave to this change. Additionally, "Le Mas des Agriculteurs" would like to minimize the ratio of demand ordered from external suppliers by negotiating with the internal smallholders. This is to ensure that local farmers get more demand.

A. *Cost analysis*

The first changed variable is that of the unit cost of the product. We analyze the solutions generated by applying ratio discounts to the original unit price of each smallholder.

Figure 2 shows the percentage of demand ordered from the smallholders when S_1, S_2, and S_3 offer additional discounts, respectively. It can be noted that there is no significant increase in demand from S_1 as they lower their prices since the model already orders from this producer at near maximum capacity. As for S_2, there is a significant jump in their demand proportion once they lower their prices by 20\$. This increase in demand is taken from the orders placed at S_1 since the price of S_2 can now compete against them. As for S_3, there is a steady increase in demand as they offer additional discounts. This increase in demand is countered by a decrease in demand from S_1 and S_2.

The analysis of the unit price shows that lowering the prices does increase the demand ordered from that smallholder until near maximal capacity. However, this increase in demand is at the cost of other internal smallholders and not the external one since the orders from S_4 remain the same throughout the entire experiment. Therefore, negotiating the unit cost with the smallholders will not help "Le Mas des Agriculteurs" achieve its goal of minimizing the ordered quantities from external suppliers.

B. *Capacity of production analysis*

The solution of the model (Table VII) shows that the model places the orders with the maximal capacity of the smallholders at some times. Therefore, increasing the production capacity of smallholders by allocating more land to this specific product might increase the volume of placed orders. Figure 3 shows the variation of demand as the capacity of the smallholders S_1, S_2, and S_3, respectively is increased.

The figure shows that an increase in the production capacity of the smallholders leads to an increase in the proportion of orders that they receive. However, the increase in capacity in S_1 and S_2 does not lead to a decrease in the demand of S_4. Only in the case where S_3 increases their capacity of production is there a decrease in the demand placed at S_4. This might be due to the ability of S_3 to produce some products during the period where the remaining internal smallholders are not able to do so or are producing too little (from $t = 9$ till $t = 11$). Therefore, to minimize the orders placed to S_4, "Le Mas des Agriculteurs" would need to negotiate an increase in production with S_3. To ensure that S_3 does not dominate the remaining internal smallholders, they need to negotiate with S_1 and S_2 a decrease in their price, which will lead to an increase in their demand.

C. *Storage capacity and inventory holding cost analysis*

Varying the capacity of the inventory and the holding costs of the smallholders did not garner a significant change in the solution provided by the model. Therefore, negotiating these variables with the smallholders will not result in an improvement in the orders.

VI. CONCLUSION AND FUTURE WORK

In this work, we present a linear program to reduce the cost of the supplier selection and order allocation problem of the

TABLE V

STORAGE CAPACITY OF THE SMALLHOLDERS (IN TONNES) ACROSS THE PERIODS.

Storage capacity i_t^s		**Period** t											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Smallholder s	**1**	5	5	3	5	5	8	8	6	5	5	5	6
	2	3	13	5	0	5	2	6	10	0	15	10	2
	3	5	6	12	3	12	11	2	2	6	14	13	7
	4	0	0	0	0	0	0	0	0	0	0	0	0

TABLE VI

UNIT HOLDING COSTS PER PERIOD (IN €/TONNE/ PERIOD) OF THE SMALLHOLDERS.

Unit holding cost h_t^s		**Period** t											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Smallholder s	**1**	38.8	45.2	46.8	50.8	62.4	62.8	67.2	62.4	57.6	47.2	44.4	33.6
	2	20	33.6	38	50.8	53.2	56.8	56.8	54.8	51.2	43.6	34	28.4
	3	9.6	14.8	19.6	29.2	44.8	60	62	56	43.6	23.6	17.6	9.6
	4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

TABLE VII

RESULTS OF THE NUMERICAL EXAMPLE.

Period t	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Demand d_t	15	15	20	25	27	30	35	30	25	20	22	15
D_t^1	5	15	20	20	13		5	6	1	5		
D_t^2	2			5	14	30	16	4	13			
D_t^3	8						14	20	11	15		11
D_t^4											22	4
$\sum_{s=1}^{\lvert S\rvert} D_t^s$	15	15	20	25	27	30	35	30	25	20	22	15
I_t^1					2	2	7	6	5			
I_t^2					2	2	6	10				
I_t^3							2	2	6	1	11	
$\sum_{s=1}^{\lvert S\rvert} I_t^s$					4	4	15	18	11	1	11	
Q_t^1	5	15	20	20	15		10	5				
Q_t^2	2			5	16	30	20	8	3			
Q_t^3	8						16	20	15	10	10	
Q_t^4											22	4
$\sum_{s=1}^{S} Q_t^s$	15	15	20	25	31	30	46	33	18	10	32	4

***TC* = 411 467.8€.**

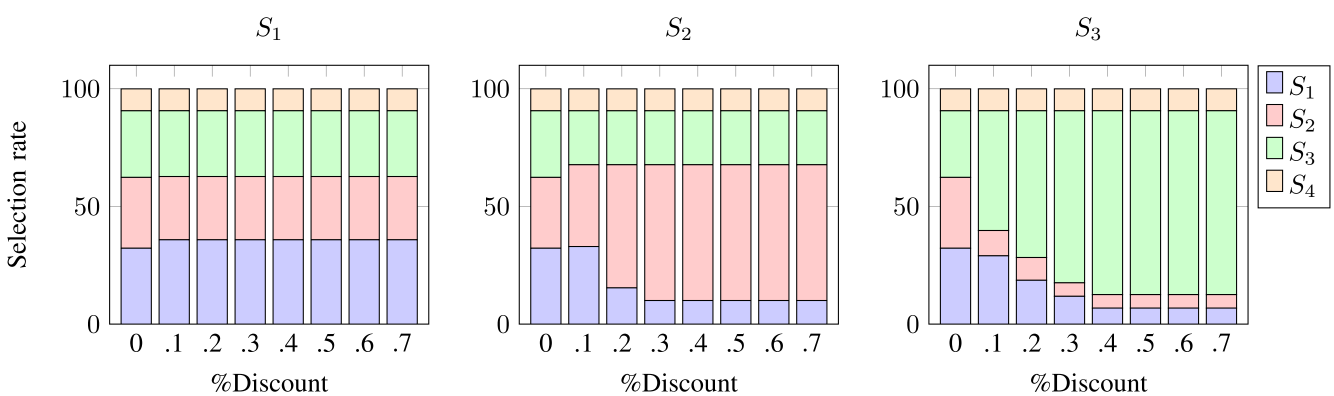

Fig. 2. Selection rates when discounts are applied to the pricing of the smallholders.

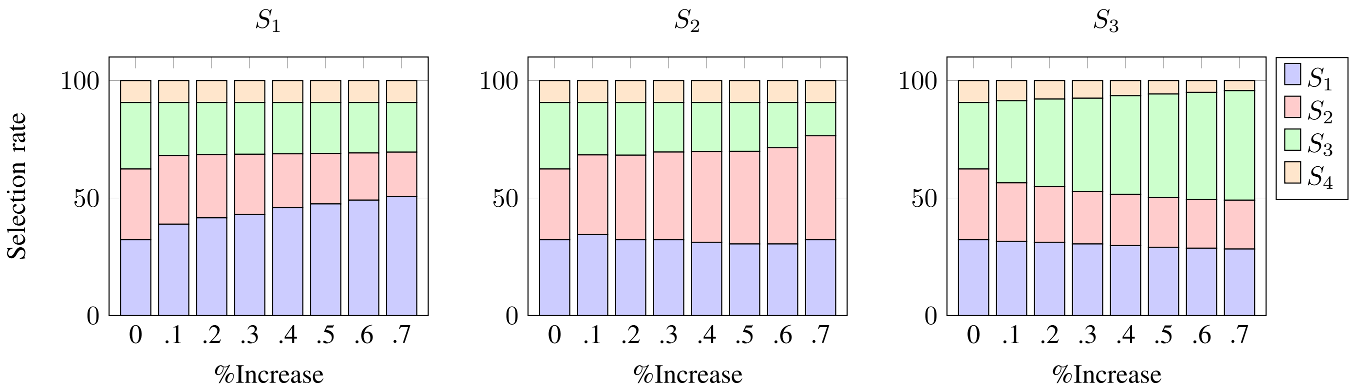

Fig. 3. Selection rates when smallholders increase their production capacity.

potato produce for "Le Mas des Agriculteurs". In this study, there are internal suppliers and an external one. Each supplier has characteristics such as production capacity, inventory holding cost, storage capacity, and quantity-dependent pricing. The goal of "Le Mas des Agriculteurs" is to plan the potato orders one year in advance and to meet all the demands of the market. We showcase an instance of the problem and study how the solutions differ when we vary the considered parameters. This would allow us to advise the internal suppliers on what to change in their pricing so that the volume of orders placed from them is maximized. This work, however, still needs fine-tuning to take into account environmental factors and the uncertainties due to the rolling horizon (demand, yield, lead-times, etc.). The future intention is to track the geographical distance of each supplier from "Le Mas des Agriculteurs," and the amount of water used for their crops and integrate these. This would allow us to add environmental constraints and uncertainties to the model, follow the trend of green supply planning, and ensure the benefit of "Le Mas des Agriculteurs", the smallholders, and the environment.

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