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Finding the Perfect Match: Smallholder Selection in Short Food Supply Chains

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Abstract

In the short-food supply chain, retailers have to make critical decisions when choosing which farmer to buy the produce from. Moreover, planning for long periods of time further complicates this task. This work presents a linear program integrated in a rolling horizon to assist retailers in planning their orders from different suppliers and knowing when to place them. The model is developed to overcome the single-item, multi-sourcing, capacitated lot-sizing problem and plan the long-term orders for the retailer. When tested, the model successfully planned the orders, deliveries, and inventories of the different suppliers while minimizing the cost for the retailer. Finally, when tested for instances of increased complexity, the model managed to find the solutions within an acceptable execution time.

Keywords: Supplier Selection; Lot Sizing; Smallholder; Supply Chain; Rolling horizon

1. Introduction and problem description

In companies, retailers have to plan their orders tediously for their suppliers to ensure the meeting of the demand of the market and the satisfaction of their clients. In the food supply chain, retailers would need to place the orders months in advance so that the farmers have the time to plant and grow the produce if needed. This raises the problem of supplier selection and order allocation [Aouadni et al. \(2019\)](#); [Naqvi and Amin \(2021\)](#), whereby the retailers have to plan the order they place to their supplier while considering their objectives, such as lowering the costs.

This work falls under the [SMALLDERS project](#), which attempts to assist all actors of the short food supply chain. The project studies the different needs of the short food supply chain ([Longo et al., 2023](#); [Miranda et al., 2023](#); [Amamou et al., 2023](#); [Stefanini et al., 2023](#)), develops models to study and enhance their performance ([Francesco Longo and Solina, 2024](#); [Longo et al., 2024](#);

[Germanos et al., 2023a](#); [Mallek-Daclin et al., 2024](#)), and encourages these actors to adopt these technologies ([Cimino et al., 2024](#)). In this project, we partnered as well with "Le Mas des Agriculteurs", an agriculture retailer that sources fruits and vegetables from the smallholders of the Gard region, South of France, to sell to hospitals, schools, and other organizations. Therefore, it is essential for "Le Mas des Agriculteurs" to vigorously plan all the orders to ensure that the students in schools and the patients in the hospitals are well fed. This institution sources its produce from different farmers, each with their own prices and capacities.

Additionally, when these local smallholders cannot meet the demand of "Le Mas des Agriculteurs" clients due to their limited production capacity, the latter would purchase the produce from an external supplier at a higher cost. The main challenge that "Le Mas des Agriculteurs" currently faces is choosing when and where to place orders with its suppliers. And since "Le Mas des Agricul-



teurs" engages in contract farming, whereby the association places its initial order twelve months in advance, the order planning becomes a more precise task. Furthermore, once an order is placed, "Le Mas des Agriculteurs" cannot cancel it or lower the quantity ordered. Otherwise, they would be penalized. Once an order is placed, "Le Mas des Agriculteurs" can only add to the quantity ordered. Finally, when needed, "Le Mas des Agriculteurs" can increase the quantity they need to be delivered from a farmer up to six months before the planned delivery date, otherwise the farmer may not have the time to meet the additional ordered quantity. To overcome this challenge, we develop an optimization model that considers the dynamic demand of the clients of "Le Mas des Agriculteurs," along with the different characteristics of the suppliers. These characteristics include:

- Dynamic production capacity: Each smallholder has their 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 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 unit price for the produce;
- Unit change cost: Each smallholder has their own unit change cost, an additional cost that "Le Mas des Agriculteurs" has to pay alongside the unit price if they decide to add to the previously ordered quantities.

Furthermore, we integrate the rolling horizon approach to help "Le Mas des Agriculteurs" continuously plan the upcoming orders. Many optimization problems in the industrial engineering field involve planning actions across multiple time periods. For example, in this work, it is required to plan the orders of "Le Mas des Agriculteurs" for every month of the year for multiple years. The length of time that the decisions need to be made is referred to as planning horizon (Swamidass, 2000). However, once the planning horizon becomes too long, the optimization problem becomes too complex to solve. This also occurs when the future is uncertain, i.e., the client's demand for the upcoming ten years is unknown, then forecasting the future is a costly activity (Sethi and Sorger, 1991). The rolling horizon is a method for overcoming long planning periods and unknown future parameters. The method dissects the planning horizon into time steps and then focuses on decision-making for the subset of closest time steps, called

the "rolling window." Once enough time has passed, the rolling window "slides" into the next set of time steps. In some scenarios, the notion of "frozen periods" is added to the rolling horizon planning, whereby decisions cannot be changed during these periods. These periods usually fall between the current time and the rolling window periods and offer some stability to the solution when new information is added to the system. In this work, the frozen periods allow enough time for the farmers to plant and farm their produce.

Figure 1 illustrates this procedure for the case of "Le Mas des Agriculteurs". In this scenario, at month W , the planning horizon starts at $W + 6$ and extends till month $W + 12$. This allows the model to place new orders up to one year in advance and does not allow it to modify the order in the next six months to match the constraint imposed by the farmers.

The rest of this work is divided as follows: we review some of the methods developed for supplier selection in Section 2, we describe the proposed approach in Section 3, we showcase a case study in Section 4, to finally conclude in Section 5.

2. Literature Review

The supplier selection and order allocation problems are heavily covered in the research operation field. Multiple models have been developed to assist the retailers in this problem, such as linear programming (Modibbo et al., 2022; Bettayeb et al., 2021; Dimiyati, 2020), non-linear programming (Esmaeili-Najafabadi et al., 2021; Yousefi et al., 2021; Lamba and Singh, 2019), and other decision-making techniques (Aouadni and Euchi, 2022; Thevenin et al., 2022; Alejo-Reyes et al., 2020). However, few of the works integrated a rolling horizon approach to their model. We cite some of these works below.

Mateo-Fornés et al. (2023) focused on managing the cold storage of fresh fruits, which will be dehydrated later on. They modeled the storage of different apple varieties and cold storage types and integrated uncertainty in the conversion rate from fresh fruits to dehydrated ones. Their goal was to minimize different costs, such as transportation and storage. They developed a two-stage stochastic programming model that firstly aids in the selection of fruits bought from different producers and then aids in storage decisions. Their model lowered the costs by an average of 6.4%.

Noh and Hwang (2023) focused on the energy supply chain management field that is facing two challenges: the tightened environmental regulations and the various uncertainties caused by various factors. The work focuses on a single power plant and multiple fossil fuel suppliers while considering uncertain energy demands. To do so, the authors developed a mixed integer linear program that operates under a rolling horizon model and helps choose which fossil fuel supplier to purchase from. The authors added the rolling horizon method to their work to handle

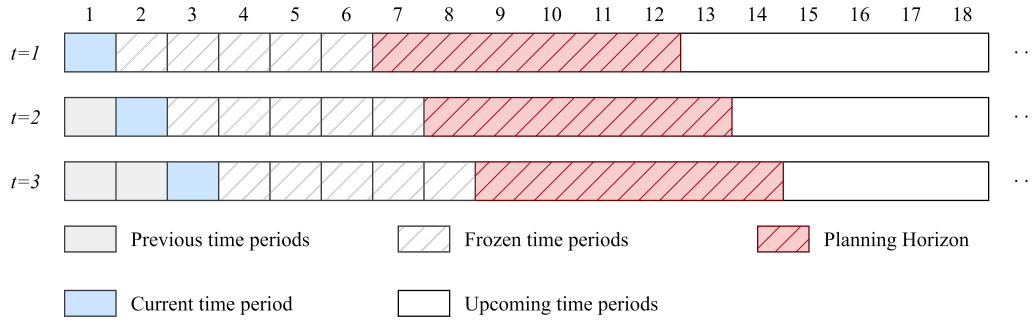


Figure 1. Rolling horizon representation for "Le Mas des Agriculteurs" scenario

uncertainty. They performed a sensitivity analysis, which showed the effectiveness of their RH_c when dealing with uncertainty, along with the trade-off between the costs and the sustainability of this field.

Badejo and Ierapetritou (2023) modeled a four-tier supply chain network as a directed graph. Their work attempts to minimize costs while considering disruption and demand uncertainty. To do so, the authors developed a two-stage stochastic model that integrates mixed integer programming models and tested it on a rolling horizon. Their model outperforms the deterministic one when disruptions are introduced to the system.

Even though researchers using multiple methods and in different fields have covered the problem of supplier selection and order allocation, no work has been developed to tackle the problem for agri-food retailers who specialize in dealing with local smallholders while integrating the rolling horizon approach. Therefore, this work puts forward such model that would be vital to the retailers who face the same challenges as "Le Mas des Agriculteurs".

3. Proposed resolving approach

This paper builds over the model developed in Germanos et al. (2023b), whereby, in this work, we model more precisely the scenario of "Le Mas des Agriculteurs" by integrating the rolling horizon approach in the computations.

In this formulation, we follow a multi-sourcing policy whereby each supplier, or smallholder, has their dynamic production capacity and pricing policy. Each smallholder also has a dynamic storage capacity with their own holding cost, allowing orders to be stored in their inventories until the planned delivery date. Each smallholder has their own unit change cost, an additional cost that "Le Mas des Agriculteurs" has to take charge of if they change a previously agreed upon order. Finally, the model does not allow backlogging, and the demand of the clients must be fully met at every time period. The following linear program models the studied problem. It uses the notation introduced in Table 1.

$$TC: \min \sum_{w \in \mathcal{W}} \sum_{s \in \mathcal{S}} (o_s \cdot Y_w^s + p_s \cdot Q_w^s + \lambda_w^s \cdot \delta_w^s + h_w^s I_w^s) \quad (1)$$

Table 1. Notations.

Parameters	
\mathcal{W}	planning horizon window
\mathcal{S}	set of smallholders
s	index of smallholders, $s \in \mathcal{S}$
w	index of the period, $w \in \mathcal{W}$
d_w	monthly known demand
p_s	unit selling price of smallholder s
o_s	ordering cost of smallholder s
h_w^s	unit inventory holding cost of smallholder s at period w
λ_w^s	unit change cost of smallholder s at period w
c_w^s	production capacity limit of smallholder s at period w
i_w^s	storage capacity of smallholder s at period w
Q_w^s	integer indicating the previously planned total quantity to order from smallholder s at period w
M	Big M
Variables	
D_w^s	integer decision variable that gives the updated delivered quantity from smallholder s at the end of period w
Q_w^s	integer decision variable that gives updated the total quantity to order from smallholder s at period w
I_w^s	updated inventory level of smallholder s at the end of period w
δ_w^s	the change in ordered quantity from smallholder s at time w between the previously ordered quantity Q_w^s and the updated one Q_w^s
Y_w^s	binary variable that indicates if an order was placed with smallholder s at time w

subject to constraints:

$$I_w^s \geq I_{w-1}^s + (Q_w^s - D_w^s) \quad \forall s \in \mathcal{S}, \forall w \in \mathcal{W} \quad (2)$$

$$\sum_{s \in \mathcal{S}} D_w^s \geq d_w \quad \forall w \in \mathcal{W} \quad (3)$$

$$I_w^s \leq i_w^s \quad \forall s \in \mathcal{S}, \forall w \in \mathcal{W} \quad (4)$$

$$Q_w^s \leq c_w^s \quad \forall s \in \mathcal{S}, \forall w \in \mathcal{W} \quad (5)$$

$$Q_w^s \geq Q_w^s \quad \forall s \in \mathcal{S}, \forall w \in \mathcal{W} \quad (6)$$

$$\delta_w^S \geq Q_w^S - Q_w^S \quad \forall s \in \mathcal{S}, \forall w \in \mathcal{W}_{1 \rightarrow |\mathcal{W}-1|} \quad (7)$$

$$Q_w^S \leq M \cdot Y_w^S \quad \forall s \in \mathcal{S}, \forall w \in \mathcal{W} \quad (8)$$

$$I_w^S \geq 0 \quad \forall s \in \mathcal{S}, \forall w \in \mathcal{W} \quad (9)$$

$$I_w^{|\mathcal{S}|} = 0 \quad \forall w \in \mathcal{W} \quad (10)$$

$$Q_w^S, D_w^S \geq 0 \quad \forall s \in \mathcal{S}, \forall w \in \mathcal{W} \quad (11)$$

In this formulation, the objective function (1) minimizes the different costs (ordering, purchasing, changing, and holding) of the solution. Constraints (2) calculates the inventory level at each period $\forall w \in \mathcal{W}$ for all the suppliers $\forall s \in \mathcal{S}$. Constraints (3) ensures that the delivered quantities from the meet the demands of the clients at each period $\forall w \in \mathcal{W}$. Constraints (4) ensure that the smallholders' storage capacity is respected at each time period. Constraints (5) ensure that the smallholders' production capacity is respected at each time period. Constraints (6) ensure that the model can only add to the previously agreed upon order quantities. Constraints (7) compute the quantities that were added to the order up until month $W+11$, as month $W+12$ was just added to the planning horizon. Constraints (8) ensure the validity of the binary variables Y_w^S . Constraints (9) ensure that the inventory levels stay positive, and constraints (10) ensure that the inventory of the last supplier, which is the external farmer, remains zero as they do not offer storage facilities. Finally, constraints (11) ensure that the ordered Q_w^S and delivered D_w^S quantities remain positive. This formulation of the problem follows the C/G/C/G representation (constant ordering cost, changing holding cost, constant production cost, and changing capacities) as explained by Bitran and Yanasse (1982) and Brahimi et al. (2006). This formulation is a generalization of the C/G/Z/NI representation, which is itself an NP-hard problem. Therefore, the former formulation of the problem is NP-hard as well.

In order to integrate this LP into the rolling horizon approach, we implement Algorithm 1.

Algorithm 1 Proposed Rolling Horizon

Require: $d_w, p_s, o_s, h_w^s, \lambda_w^s, c_w^s, i_w^s$
for every planning horizon in \mathcal{W} **do**
 Extract $d_w, h_w^s, \lambda_w^s, c_w^s, i_w^s$ of \mathcal{W}
 Optimize $TC(D_w^S, Q_w^S)$
 $D_w^S \leftarrow D_w^S$
end for

As a first step, the algorithm considers what has already been planned by "Le Mas des Agriculteurs" or any other users. It would then generate a solution for the current planning horizon and update the ordered, delivered, and stored quantities for each time period by considering the changes that would be made to the original plan. Then, during the next month, the planning horizon, the orders, and the costs are updated. This process can be repeated infinitely.

Table 2. Purchasing (in €/Tonne) and ordering costs (in €) of suppliers

		unit purchasing cost p_s	ordering cost o_s
Smallholder s	1	420	550
	2	470	500
	3	500	650
	4	550	750

Table 3. Inventory holding cost (in €/Tonne/period), change cost (in €) production capacity of suppliers

		Holding cost h_w^s								
Period w		1	2	3	4	5	6	7	8	9
Smallholder s	1	35	35	40	42	43	40	44	46	50
	2	40	42	42	41	43	47	50	52	50
	3	44	44	45	44	45	45	53	52	53
	4	∅	∅	∅	∅	∅	∅	∅	∅	∅
		Change cost λ_w^s								
Period w		1	2	3	4	5	6	7	8	9
Smallholder s	1	300	250	280	310	290	320	290	300	280
	2	400	410	420	400	410	420	390	410	440
	3	500	460	440	450	470	500	510	520	510
	4	600	570	560	580	590	600	570	560	570

Table 4. Production capacity (in Tonne) and storage capacity (in Tonne) of suppliers

		Production capacity c_w^s								
Period w		1	2	3	4	5	6	7	8	9
Smallholder s	1	28	11	20	18	27	14	14	19	13
	2	19	19	11	13	20	21	20	16	12
	3	28	35	52	51	48	40	33	43	53
	4	∞	∞	∞	∞	∞	∞	∞	∞	∞
		Storage capacity i_w^s								
Period w		1	2	3	4	5	6	7	8	9
Smallholder s	1	22	24	10	25	28	23	28	27	18
	2	17	27	24	30	29	23	14	36	34
	3	10	36	29	11	30	37	25	26	36
	4	∅	∅	∅	∅	∅	∅	∅	∅	∅

4. Case Study

We evaluate the effectiveness of our proposed model using a scenario influenced by the case study of "Le Mas des Agriculteurs". The scenario involves four suppliers, whereby the fourth one represents the external supplier that has an infinite production capacity but no inventory. Table 2 details the purchasing and ordering costs of the suppliers. Table 3 shows the suppliers' inventory holding cost and their change cost.

Table 4 lists the production capacities and storage capacities of the suppliers.

To solve this instance, the model was developed in Python, and the solver for the LP was CPLEX. The test was carried out with a 12th Gen Intel(R) Core(TM) i9-12900H processor and 64 GB of RAM. Table 5 shows the clients' demand and the allocated orders for each smallholder.

The solution shows the sliding planning horizon and the slight changes the model had to make to previous orders to account for the new ones. The changed values are underlined. The cost of planning for the months $w = 1$ till $w = 6$ is 237,930 €. This plan was calculated as an initial

Table 5. Distribution of orders, deliveries, and inventories of the solution generated by the model

	Period w	1	2	3	4	5	6	
	Demand d_w	74	99	88	95	55	61	
Delivered quantity	D_w^1	27	7	25	18	27	14	
	D_w^2	19	19	11	13	20	21	
	D_w^3	28	35	52	51	8	26	
	D_w^4		38		13			
Ordered quantity	Q_w^1	28	11	20	18	27	14	
	Q_w^2	19	19	11	13	20	21	
	Q_w^3	28	35	52	51	8	26	
	Q_w^4		38		13			
Stored quantity	I_w^1	1	5					
	I_w^2							
	I_w^3							
	Period w	2	3	4	5	6	7	
	Demand d_w	99	88	95	55	61	71	
Delivered quantity	D_w^1	7	25	18	27	<u>10</u>	18	
	D_w^2	19	11	13	20	21	20	
	D_w^3	35	52	51	8	<u>30</u>	33	
	D_w^4	38		13				
Ordered quantity	Q_w^1	11	20	18	27	14	14	
	Q_w^2	19	11	13	20	21	20	
	Q_w^3	35	52	51	8	<u>30</u>	33	
	Q_w^4	38		13				
Stored quantity	I_w^1	5				<u>4</u>		
	I_w^2							
	I_w^3							
	Period w	3	4	5	6	7	8	
	Demand d_w	88	95	55	61	71	32	
Delivered quantity	D_w^1		25	18	27	10	18	19
	D_w^2		11	13	20	21	20	13
	D_w^3		52	51	8	30	33	
	4			13				
Ordered quantity	Q_w^1		20	18	27	14	14	19
	Q_w^2		11	13	20	21	20	13
	Q_w^3		52	51	8	30	33	
	Q_w^4			13				
Stored quantity	I_w^1					4		
	I_w^2							
	I_w^3							
	Period w	4	5	6	7	8	9	
	Demand d_w	95	55	61	71	32	89	
Delivered quantity	D_w^1		18	27	10	18	<u>8</u>	24
	D_w^2		13	20	21	20	<u>16</u>	12
	D_w^3		51	8	30	33	<u>8</u>	53
	D_w^4		13					
Ordered quantity	Q_w^1		18	27	14	14	19	13
	Q_w^2		13	20	21	20	<u>16</u>	12
	Q_w^3		51	8	30	33	<u>8</u>	53
	Q_w^4		13					
Stored quantity	I_w^1				4		<u>11</u>	
	I_w^2							
	I_w^3							

plan using the model and by disregarding the change costs. The cost of planning for the months of $w = 2$ till $w = 7$ was 237, 145 €. This includes the change cost of Q_6^3 . The cost of planning the months $w = 3$ till $w = 8$ was 197, 710 €.

Finally, the cost of planning the months $w = 4$ till $w = 9$ was 202, 306 € including the cost of the changes made to the plan of month $w = 8$.

Furthermore, the applicability of this model to larger

Table 6. Minimum, average, and maximum execution time (in seconds) to find the solution of the entire horizon for different horizon lengths and number of smallholders

	Horizon length											
	20			30			40			50		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
$ S = 5$	0.02	0.08	0.13	0.07	0.17	0.32	0.11	0.19	0.28	0.14	0.25	0.34
$ S = 6$	0.02	0.09	0.14	0.09	0.18	0.25	0.11	0.21	0.30	0.17	0.34	0.42
$ S = 7$	0.17	0.10	0.17	0.11	0.18	0.28	0.14	0.24	0.31	0.31	0.44	0.66
$ S = 8$	0.03	0.11	0.17	0.13	0.22	0.30	0.16	0.26	0.35	0.21	0.35	0.50
$ S = 9$	0.03	0.11	0.16	0.14	0.22	0.33	0.17	0.37	0.64	0.27	0.40	0.50
$ S = 10$	0.05	0.13	0.17	0.20	0.26	0.35	0.25	0.31	0.36	0.35	0.46	0.80

problems is inspected to ensure its efficacy when planning for larger retailers. To do so, we time the execution time of the model when tested on instances of varying smallholders and rolling horizon size. However, the planning horizon was always set to 6 periods. The instances were generated using a Monte Carlo simulation approach, and the experiment on each instance size was repeated 15 times to ensure the validity of the generated numbers. We report the minimum, maximum, and average time needed to generate the solution of all the planning horizons for a given instance in Table 6.

The results show an increase in time when the number of smallholders is increased, as well as an increase in the total horizon length. This comes to no surprise, as the LP would need to add more variables and constraints to solve instances that include more smallholders, and the model would need to solve a bigger number of planning horizons for overall longer horizons. However, even though the total execution time of the model is increasing with the complexity of the instance, it remains an acceptable computational time.

5. Conclusion

In this work, we tackle the supplier selection and order allocation problems for "Le Mas des Agriculteurs". The modeled scenario takes into account the dynamic demand of the clients and the dynamic characteristics of the smallholders. The model also takes into account a rolling horizon approach, which tolerates alterations to previous orders placed with smallholders in order to satisfy future demand with minimal costs. The model was tested on a case study inspired by real-life data, and it showed its ability to plan the ordered quantities, the delivered quantities, and the inventories across the planning period. Additionally, simulations were performed to test the execution time of the model. The experiments show that the computational time increases depending on the number of periods and smallholders but remains an acceptable time.

Although the developed model takes into consideration the dynamic capacities and pricing of the producers, as well as the dynamic demand of the clients, the model fails to take into consideration the uncertainty of these parameters. Future work should attempt to integrate this uncertainty into the model to offer better solutions to

the retailers.

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