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***Abstract.*** Recent market studies showed that the demand for organic and local agrifood products is increasing despite their higher prices. The agribusiness actors should therefore rethink the supply chain configuration to cope with new market trends characterized by the rise of the organic segment and the increase of consumers' preference to more local products. This study focuses on the olive oil sector and proposes a mixed-integer non-linear optimization model for the design of olive oil supply chains while incorporating organic and conventional market segments and considering, for each segment, a supply chain proximity- and price-sensitive demand. The model is developed with the collaboration of olive oil producers in the Mediterranean area. Thanks to this industrial collaboration, we account for real-world practices and constraints and apply the model to a realistic case study. We first linearize the model and show that it can be efficiently solved with commercial optimization softwares. Based on numerical experiments, we derive a series of managerial insights that are applicable to the considered case study, some of them are not intuitive. For instance, we show that an increase in consumers' preference to more local products may lead the producer to offer products with a more global supply chain. The conventional product variety may be produced with a more local supply chain than the organic (premium) variety. Finally, offering a mix of organic and conventional varieties instead of only one variety would lead to implementing a more local supply chain.

***Keywords:*** Agrifood; Supply chain design; Olive oil; Organic product; Local product.

## 1. Introduction

The management of agrifood supply chains has recently received an increasing attention in the operations management and supply chain (SC) literature. The agrifood SCs differ from classical manufacturing SCs in many ways, including specific production characteristics and supply constraints (Esteso et al. 2018, Behzadi et al. 2017, Borodin et al. 2016). The consumers' purchase behaviour for agrifood products has considerably changed in the last years. According to The Business Research Company's report (TBRC 2020), the demand for local and organic food production is increasing. The report outlines that consumers are willing to pay a little more for something they recognize as healthy and, with the coronavirus crisis, a lot of focus on supporting local brands is being emphasized as well. There is a consensus in the literature that organic and local labels are two new attributes that govern the purchasing decisions for agrifood products. The emergence of organic products, despite their higher prices compared to conventional products, is highlighted by many authors. In May 2020, the organic food and drink sales in the UK increased by 6.1%, almost doubled from the previous year's growth of 3.2% (TBRC 2020). Sazvar et al. (2018) show that a substitution can be observed between conventional products towards organic products thanks to a better communication about organic product benefits for the environment and the consumers' health. The consumers are also increasingly interested in more local agrifood products, i.e., products resulting from shorter SCs, as against products obtained with more global (longer) SCs. Almost 90% of consumers think local foods are very or somewhat important (Tropp 2014). Scalco et al. (2020) highlight that there is greater demand for products coming from a model that contrasts with the global-scale production model. In a recent empirical study on the French agrifood sector, Palacios-Argüello et al. (2020) show that an increasing number of consumers are switching to organic and local products, as such products reflect more qualitative and healthier alternatives. These new trends in consumers' behaviour require to rethink and adapt agrifood SC strategies.

In particular, the olive oil SCs are highly impacted by these market changes. Panico et al. (2014) show that information on origin and organic certification affect consumers' preferences for olive oil. According to many authors (Yangui et al. 2014, Romo-Muñoz et al. 2015, Cacchiarelli et al. 2016, Boncinelli et al. 2016), the attributes that most influence the olive oil demand are the final price, the olive oil origin (which is one of the main factors that characterize the SC proximity level), and the organic certification. Other studies confirm the impact of organic labelling on the olive oil selling prices and customers' willingness to pay. For instance, Vlontzos and Duquenne (2014) show that Greek consumers accept payment premiums for organic olive oils. The olive oil SCs should therefore account for the rise of the organic segment and the consumers' preference to more local products.

The olive oil is becoming an important agrifood product worldwide. The olive oil consumption that was traditionally restricted to the Mediterranean area (mainly, Spain, Tunisia, Greece, and Italy) is currently increasing in non-producing countries or emerging markets (especially, U.S., Canada, Australia, China, Japan, Argentina, and Brazil) (Karanikolas et al. 2018, Roselli et al. 2016, Sayadi et al. 2016). The average world consumption has almost doubled over the past 25 years. The olive oil demand is also increasing in new European markets (e.g., the French market). In 2019, the olive oil consumption in France was approximately 108,000 tons and only 5,500 tons were produced in France (Afidol 2019). Many Spanish and Tunisian olive oil producers are targeting the French market. There are also a few French producers in South-East France. Most of these producers focus on the premium segment by offering a local organic olive oil. Given the new changes in consumers' behaviour, the design of olive oil SCs to target a given market (the French market in our case study) requires addressing the following questions:

- How to design the olive oil SC (selection of the olives' suppliers given the supply constraints in each area, and location of the olive oil production facility) to match the SC proximity level and product characteristics with market requirements?
- What is the impact of consumers' sensitivity to the SC proximity level?
- What is the impact of offering a mix of organic and conventional varieties?

This paper investigates the above questions faced by olive oil producers. We formulate and analyze the following problem. An olive oil producer targets a given market segmented into organic and conventional consumers, and the demand in each segment depends on the SC proximity level and price. The producer needs to decide whether to offer a conventional variety, an organic variety or a mix of both varieties, and to design the SC accordingly while selecting the location and capacity of the production facility and choosing the supply zones. Our study contributes to both theory and practice. On the theoretical side, we develop a SC design model that is adapted to the olive oil sector while considering two market segments (organic and conventional segments), capturing the demand sensitivity to SC proximity level (i.e., a more local SC leads to a higher demand), and incorporating pricing decisions. This is the first study to investigate the SC design problem form this perspective. On the practical side, our proposed model fits with real-world situations faced by olive oil producers and investors. Thanks to our collaboration with olive oil producers in Tunisia, Spain and France, we account for the specific features of the olive oil industry in terms of production characteristics, supply constraints, and market characteristics. This industrial collaboration also allows us to apply our model to a realistic case study and to use realistic data in our experiments. We perform numerical analyses and deduce a set of managerial insights that are useful for olive oil producers. These insights investigate the interplay of consumers' sensitivity to SC proximity level, the mix of organic and conventional olive oil varieties, the prices, the demand, and the profit.

Section 2 reviews the relevant literature. In section 3, we present the modeling framework and describe the case study. The optimization model is formulated in Section 4. In Section 5, we show how to solve the model and discuss the computational performance. Section 6 is dedicated to the numerical analysis and managerial insights. We finally conclude and discuss future work directions in Section 7.

## 2. Literature review

The extant literature on agrifood SC management focuses mainly on production planning, storage, and distribution problems. For instance, the production management and planning problems have been studied by Allen and Schuster (2004) for a concord grape and juice SC, Blanco et al. (2005) for a multi-commodity fruits/juices (apples and pears) SC, and Merrill (2007) for a premium-brand tomato SC. Bohle et al. (2010) investigated the problem of harvest planning in a grape (wine) SC under yield uncertainty. Huh and Lall (2013) studied how a farmer decides to allocate his land among different crops with varying water requirements. Wiedenmann and Geldermann (2015) proposed a supply planning model for linseed oil processor in a polymers production SC. Boyabatli et al. (2017) studied the optimal onetime processing and (output) storage capacity investment decisions when both input and output spot prices as well as production yield are uncertain. Boyabatli et al. (2019) examined the crop planning decision in sustainable agriculture. The research stream described above is different from our study in many ways. First, it does not deal with the SC design problem. Second, it ignores the effects of the organic label and the SC proximity level. In what follows, we first review the most related papers to our work and then discuss the empirical literature on the interplay between the olive oil demand, the price, the organic label, and the SC proximity.

### 2.1. Related works

An olive oil SC typically consists of farmers (suppliers of olives), a producer (extracts the oil from olives), and distributors. We develop and study an olive oil SC design model. We first focus on the problem of SC design in agrifood SCs, not specifically for olive oil. Few papers dealt with this problem. Latorre-Biel et al. (2014) proposed a decision support methodology for improving the design and management of an olive oil manufacturing facility based on a Petri net model of the system, the simulation of its behaviour under a selected set of alternative configurations, and the choice of the most promising one using optimization algorithms (metaheuristics, decomposition based on the divide and conquer approach). Indeed, a first solving approach consists in considering all the undetermined parameters of the Petri net model simultaneously, but this leads to a complex optimization problem with a large search space. The problem is then solved using metaheuristics procedures, because the complete exploration of the feasible set is not practical. An alternative approach consists in selecting manually some of the undefined parameters of the Petri net, which leads to subproblems with less complexity. These subproblems can be solved independently. The solutions to the subproblems are then combined into the solution for the original problem. This approach is called *"divide and conquer"*. Cruz et al. (2019) developed a mixed-integer linear programming model to address the strategic-tactical decisions of capacity definition, processing technology selection, and product flows in sugar beet SCs. The objective is to maximize the expected net present value. The authors consider product perishability, flexible storage strategies, and reverse logistics operations. Supply and demand uncertainties are considered using scenarios tree. We were unable to find other relevant papers on agrifood SC design in operations and SC management journals.

We now move to the olive oil SC literature. The extant works on olive oil SCs typically consider a given olive oil production facility and focus on olives supply decisions. Kazaz (2004) investigated the production planning decisions under yield and demand uncertainties. While a traditional olive oil producer purchases olives from farmers, a recent practice consists of leasing farm space to increase profits. The proposed model determines the optimal amount of farm space to be leased in the first stage, the quantity of olives to be purchased from other growers, and the total amount of olive oil to be produced in the second stage. Kazaz (2008) studied the sale price and the production quantity under supply uncertainty. The author considered a firm that initially leases a farm space to grow fruit, in particular olives. The realized amount of fruit supply fluctuates, for example due to weather conditions and diseases. At the end of the growing season, the firm makes two decisions: the amount of realized supply to be converted into finished product and the amount of additional supply to purchase from other growers. The second opportunity to purchase from other growers occurs at a unit cost that depends on the realized supply. Two pricing models are considered. The early pricing model allows determining the sale price when the leasing agreement is made, whereas the postponed pricing model sets the sale price after observing the realized supply. Kazaz and Webster (2011) proposed a single-period production planning model that maximizes the expected return for a Turkish olive oil SC by determining the optimal amount of space to be leased for production and the quantity of olives to be provided from external sources under yield and yield-dependent cost uncertainties. It is important to note that none of the above papers deal with the design of olive oil SCs or consider the organic variety and the consumers' sensitivity to SC proximity.

### 2.2. The interplay of olive oil ogranic label, supply chain proximity, price, and demand

The most famous label for the olive oil is the EVOO (Extra Vierge Olive Oil) label. It guarantees that the olive oil is pressed mecanically from fresh fruit and has a maximum acidity of 0.8%. The olive oil with this label represents most sales in European and emergent markets. While studying the EVOO consumers' behaviour, recent empirical studies identified three criteria that govern the purchasing decisions: the organic label, the olive oil origin, and the price. Many researchers suggested that the organic certification adds value to the olive oil (Cavallo et al. 2017, Roselli et al. 2016, 2018, Liberatore et al. 2017, Boncinelli et al. 2016, Cacchiarelli et al. 2016, Del Giudice et al. 2015, Vlontzos and Duquenne 2014). Turco (2002) reported organic price premiums ranging from 10% to as high as 100% depending on the country. However, Bonti-Ankomah and Yiridoe (2006) suggested that most consumers are not willing to pay a price premium higher than 10-20%. Based on an online pilot survey, Ballco and Gracia (2020) found that the most important olive oil attributes for consumers were price, origin of production, local production, and territory. As extensively shown in the literature, the origin of production is one of the most important aspects for EVOO consumers (Romo- Muñoz et al. 2017, Ballco et al. 2015, Cabrera et al. 2015, Yangui et al. 2014, Sottomayor et al. 2010, Fotopoulos and Krystallis 2001). The results of these empirical studies confirm the interest of considering the interplay between demand, price, organic label, and SC proximity in the design of olive oil SCs. To our knowledge, our study is first to address this problem.

## 3. Problem description and real data

We study the problem of an olive oil producer facing a market segmented into organic and conventional consumers, where the demand in each segment decreases in the SC proximity level and price. The producer needs to decide whether to offer a conventional variety, an organic variety, or a mix of both varieties, and to design the SC accordingly while selecting the location and the capacity of the olive oil production facility and choosing the suppliers of olives (farmers). To investigate this problem, we develop an olive oil SC design model that is inspired from a practical case study but can be generalized to address other situations as will be explained throughout the paper. In our case study, the producer distributes its products through a retailer located in the department of Var (region of Provence-Alpes Côte d'Azur in South-East France). The department of Var (i.e., the retailer's location) represents the demand zone. The proposed model can be used for other markets. It can also be adapted to investigate the SC design of other agrifood products that face the rise of organic market segments and proximity-sensitive consumers. However, this would require adjusting the parameters and constraints to each specific case. With these adjustments, the model could be used to study to the fruit juices (orange juice, tomato juice, apple juice, etc.) or the wines, for which there is an increasing offer of organic varieties in the market. However, the proximity level is not sufficient to understand the demand for the wine since, in this case, the production origin is not only a proximity level criterion but also a reputation criterion (e.g., the French Bordeaux wine's reputation would generate more demand and thus would allow a higher price regardless of the proximity level). We do not consider the interplay between the production origin, the product reputation, and the demand. However, since the production origin is a decision variable in our model and only one production zone can be selected, it is possible (from a modeling perspective) to extend the demand function to consider the effect of the production origin (zone) reputation. In fact, we could add a reputation-sensitivity factor, which reflects the impact of the reputation of each production zone on the demand, multiplied by the decision variable indicating whether this production zone is selected. However, it would be challenging to implement this approach in practice since some products may not have geographical indications of origin and the reputation-sensitivity factor would be difficult to estimate without a rigor marketing study.

In this section, we present the problem and modeling framework. We also provide the numerical data used in our case study to help the reader understanding the practical context.

### 3.1. Demand function

The olive oil market is segmented into organic and conventional consumers. For each segment, the demand is a function of the SC proximity level and the price. We consider an additive demand function which is widely used in the operations management literature (Huang et al. 2013). The considered demand function has the following desirable characteristics. If two products are offered at the same price but two different proximity levels, then the more local product (i.e., the product obtained with the more local SC) generates a higher demand. If two products have the same proximity level, then the one that is offered at a lower price generates a higher demand. However, since the demand depends on both proximity level and price, offering a more local product or a lower price does not necessarily lead to a higher demand. For instance, a more local product offered at a higher price may lead to a lower demand if the gain in demand resulting from the better proximity is offset by the demand loss resulting from the price increase. Thus, the trade-off between the price (cost) and the proximity level is an important decision for the firm.

Palacios-Argüello et al. (2020) analyzed the French agrifood market and found that the products can be classified into 5 categories according to the SC proximity level: local, regional, national, European, and international. Note that this classification maye be different from one product to another and from one country to another. Our model can be adjusted to consider other classifications, but this should be done for each specific practical situation.

- A **local product** (i.e., a product obtained with a local SC) refers to the case where the production is located in the same department as the demand zone (in our case study, department of Var) and the main ingredients (here, the olives) are also bought from this same department, which means that the suppliers (farmers) are located in this department. Another possible way to define a local product is to consider only the origin of the production and ignore the origin of the ingredients. According to our industrial partners, this is not realistic for the olive oil (which is 100% made from only one ingredient, the olives), but can be relevant to other products for which the consumers are not that sensitive to the origin of the ingredients. Our model can be easily modified to account for this situation.
- A **regional product** (i.e., a product obtained with a regional SC) refers to the case where the product is made in the same region as the demand zone (in our case study, region of Provence-Alpes Côte d'Azur) and the main ingredient (here, the olives) is also supplied from this same region. Similar to the case of local products, it is also possible to ignore the origin of the ingredients and define a regional product based only on the origin of the production. Our model can be modified to account for this situation.

- A **national product** (i.e., a product obtained with a national SC) refers to the case where the product is made in the same country as the demand zone (in our case study, made in France) but the required conditions for a local or a regional SC are not satisfied.
- A **European product** (i.e., a product obtained with a European SC) refers to the case where the product is made in Europe (outside France) regardless of the origin of the ingredients. The origin of the ingredients is not an important factor for SCs with low proximity level. Therefore, it is not considered in the characterization of European products. Nevertheless, our model can be adapted to the case where a European product requires that the main ingredients are also purchased from Europe.
- An **international product** (i.e., a product obtained with an international SC) refers to the case where the product is made outside Europe regardless of the origin of the ingredients.

Clearly, a local product has a better proximity (i.e., it is more local) than a regional product, and a regional product has a better proximity than a national product, which in turn is more local than a European product, which is finally more local than an international product. It is important to note that the proximity level is not equivalent to the total SC length. For the French market, for instance, an international SC may be shorter than a European SC, such as when the international product is made in North Africa. However, for most consumers, the European products are considered as more local than the North African products.

We also highlight that the consumers can easily identify the proximity level of olive oils since both the origin of the production and the origin of olives are indicated on most olive oil bottles sold in the market. According to European legislations, the olive oil origin must be mentioned on the bottle with "non-EU" if the olive oil is produced in third countries. In addition, the label "made in France" is mentioned on the bottles manufactuered in France, and most French Supermarkets have assigned stands for local and regional products. These stands are not specific to the olive oil but are usually used for several products (e.g., juices, dairy products, cakes). While the amount of space allocated to the product may influence the consumers and impact the demand, we assume here that the space is a given exogenous factor. Thus, the consumers can easily choose the olive oil in function of the proximity level. We use the subscript $i$ ($i$=1, 2, …,5) to refer to these different SC proximity levels with $i$=1 for the local SC (local product), $i$=2 for the regional SC (regional product), and so on.

For each olive oil variety (organic or conventional), the base demand represents the amount of demand obtained when the producer offers the olive oil from an international SC at the base price (i.e., standard market price). We let $p_b^o$ and $D_b^o$ (respectively, $p_b^n$ and $D_b^n$) denote the pair of base price and base demand for the organic variety (respectively, conventional variety). Relying on a more local SC leads to an increase in the base demand at rates $\beta_i^o$ and $\beta_i^n$ for the organic and the conventional varieties, respectively. Thus, offering the organic olive oil with SC length $i$ and base price $p_b^o$ generates the demand $D_i^o$=$D_b^o(1+\beta_i^o)$. For instance, a regional organic olive oil offered at base price $p_b^o$ generates the demand $D_2^o$=$D_b^o(1+\beta_2^o)$. Clearly, we have $\beta_1^o \geq \beta_2^o \geq \beta_3^o \geq \beta_4^o \geq \beta_5^o$. Since $i = 5$ refers to the international SC, $\beta_5^o = 0$. The same demand structure holds for the conventional olive oil, i.e., $D_i^n$=$D_b^n(1+\beta_i^n)$ if the product is obtained with SC length $i$ and offered at conventional base price $p_b^n$.

The producer may decide to offer a given variety with a higher price than the base price but must not exceed a given upper bound. We let $p^o$and $p^n$ represent the effective prices offered by the producer for organic and conventional varieties, respectively. As usual in the literature, we assume that the demand linearly decreases in price. We let $\alpha^o$ and $\alpha^n$ respectively denote the price-sensitivity of organic and conventional consumers. We do not impose any relation between $\alpha^o$ and $\alpha^n$, which means that $\alpha^o$ and $\alpha^n$ can take any value and that we can run the model with $\alpha^o \leq \alpha^n$ or $\alpha^n \leq \alpha^o$. In our case study, we consider that $\alpha^o \leq \alpha^n$. Indeed, since the green SC literature typically assumes that the green consumers are less sensitive to the price than the regular consumers (Asgari et al. 2021, Agi and Yan 2020, Hammami et al. 2018), it makes sense to assume that the organic consumers are also less sensitive to the price than the conventional consumers.

The effective organic and conventional demand obtained with SC length $i$ are finally given by $d_i^o$ and $d_i^n$, respectively. Figure 1 illustrates the olive oil demand function.

$$d_i^o = D_b^o(1+\beta_i^o) - \alpha^o\,(p^o - p_b^o) \qquad i = \{1, 2, \dots, 5\} \tag{1}$$

$$d_i^n = D_b^n(1+\beta_i^n) - \alpha^n\,(p^n - p_b^n) \qquad i = \{1, 2, \dots, 5\} \tag{2}$$

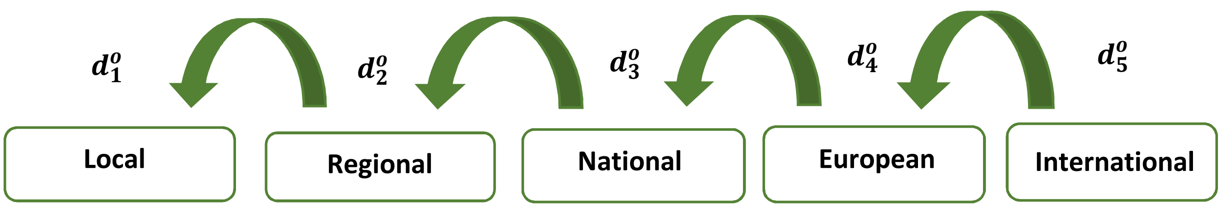

*Figure 1. Olive oil demand (example of the organic variety)*

Given the olive oil market size in South-East France, we consider in the case study that the producer can capture the base demands $D_b^n = 1561\ tons$ and $D_b^o = 207\ tons$ (these values are validated by our industrial partners). We assume the base prices $p_b^n = 5.8€/Kg$ and $p_b^o = 8.7€/Kg$ for conventional and organic olive oil, respectively. To obtain these prices, we proceeded as follows. First, we considered the prices offered in large distribution in France (we used the prices announced on the online purchase platforms of the 3 largest hypermarkets). Second, we calculated the average final price per Kg for each variety. Finally, we assumed that the hypermarkets have a net margin of 20% and deduced the base wholesale prices $p_b^n$ and $p_b^o$.

The demand sensitivity to the SC proximity level may be different between the organic and the conventional consumers (i.e., we may have $\beta_i^o \neq \beta_i^n$). Our model considers this situation. However, it is difficult to determine how $\beta_i^o$ differs from $\beta_i^n$ in practice. Given the lack of reliable data on this issue, we assume in our case study that $\beta_i^o = \beta_i^n = \beta_i$. Still, determining the value of $\beta_i$ is a challenging task in practice. A marketing analysis is required to find a reliable estimation of $\beta_i$, but this is beyond the scope of our research. Since we were not able to find any relevant study on the impact of the SC proximity level on the demand, we used the results of the empirical study conducted by Palacios-Argüello et al. (2020) on the French agrifood sector. Palacios-Argüello et al. (2020) showed that agrifood companies can increase their demand by up to 25% if they improve the greenness (there are also a few cases where more gain in demand can be obtained). In their study, the greenness was measured with different criteria, including the proximity level. We therefore use the value of 25% for $\beta_1$ (i.e., there is a 25% gain in base demand if we replace an international SC with a local SC). We then assume $\beta_2 = 20\%$, $\beta_3 = 15\%$, $\beta_4 = 5\%$, and $\beta_5 = 0\%$. Thus, the effect of the SC proximity on the demand is not linear, which is a desirable property. In fact, our industrial partners outline that the largest gain in demand occurs when we move from a European to a national SC (this explains why the biggest gap is between $\beta_4$ and $\beta_3$). Finally, to obtain the price-sensitivity of the conventional demand, we assume that the base conventional demand drops by 75% if the conventional variety is offered at the same price as the organic variety. This makes sense since most consumers will switch to buy the organic olive oil if both varieties have the same price. Therefore, we obtain $\alpha^n = 404\ €^{-1}$. Since the organic consumers are typically less sensitive to the price than the conventional consumers, we assume $\alpha^o = 101$ €$^{-1}$ (4 times lower than $\alpha^n$). We are aware that the values of $\beta_i$, $\alpha^o$, and $\alpha^n$ are difficult to estimate in practice. We shall conduct sensitivity analyses in Section 6 to assess the impact of these parameters on the model outcomes.

### 3.2. Production and supply characteristics

There is a set of potential locations $J$ (indexed by $j$) for the olive oil production facility. Each location $j$ is characterized by a production (processing) cost per Kg of olive oil ($m_j$), a distribution cost per Kg of olive oil from facility $j$ to the demand zone ($h_j$), and an annual amortized facility opening cost ($F_j$). The production cost $m_j$ does not include neither the olives purchasing cost nor the distribution cost. Our industrial partners argue that the processing cost $m_j$ is the same for both olive oil varieties. The differences between the organic and conventional varieties consist of the type and cost of olives, the olives transportation conditions, and the rates of oil extraction, as we will explain later. In our case study, we consider 3 potential production locations around the Mediterranean see: France (department of Var), Spain and Tunisia. The choice of Spain and Tunisia is motivated by three main reasons. First, most olive oils sold in France are produced in Spain and Tunisia. Second, our industrial partners argue that these two countries are the most appropriate locations for the olive oil producers targeting the French market. Third, Spain is the largest olive oil producer worldwide, and Tunisia is usually among the 6 largest producers (Afidol 2017, 2018, 2019, 2020). We present the data in Table 1 (some data in Table 1 are taken from the International Olive Council, IOC 2015).

*Table 1. Costs relative to potential production locations (€)*

| | France | Spain | Tunisia |
|---|---|---|---|
| Processing cost, $m_j$ (per Kg of olive oil) | 0.3 | 0.03 | 0.04 |
| Distribution cost, $h_j$ (per Kg of olive oil) | 0.02 | 0.05 | 0.1 |
| Annual amortized facility opening | 60, | 40, | 10, |

| | | | |
|---|---|---|---|
| cost, $F_j$ | 000 | 000 | 000 |

The producer decides the location of the production facility and the capacity to be implemented. We let $T$ denote the set of available olive oil extraction machines, indexed by $t$. We consider two types of extraction machines, with different capacities and investment costs. For each type, we present in Table 2 the total quantity of olives that can be processed per one machine per production season, denoted by $Q^t$, and the annual amortized acquisition cost, denoted by $\tau^t$ (data obtained from Addison et al. 2020). Note that the producer can acquire one or several units of each type of machine.

*Table 2. Characteristics of olive oil extraction machines*

| | Small size extraction machine | Medium size extraction machine |
|---|---|---|
| Capacity of 1 machine per season, $Q^t$ (Kg of processed olives) | 486,000 | 1,965,600 |
| Annual amortized acquisition cost of 1 machine, $\tau^t$ (€) | 10,800 | 39,200 |

Each machine (presented in Table 2) can be used to extract either organic or conventional varieties. However, the production of organic olive oil must satisfy three main conditions:

- The olive oil can be considered as organic only when the olives are organic. Note that some countries accept up to a certain percentage of conventional olives in the composition of the organic olive oil (for instance, up to 5%). This rate may differ across countries. As legislations are becoming tighter, we consider in this study that 100% of olives used to extract the organic olive oil must be certified as organic and, thus, must be bought from organic suppliers. Our model can be easily adjusted to consider other composition rates.
- The conditioning and transportation of organic olives from farmers to the production facility must satisfy specific requirements (strict cleaning conditions, small quantity of olives per container, etc.), which increases the cost per Kg of olives. This extra cost can be imputed to the purchasing cost.

- The same type of extraction machine can be used for both varieties, as explained earlier. However, the organic olive oil requires specific calibration of the extraction machine (temperature, pressure, etc.) which induces less productivity. According to our industrial partners, we approximately need $R^o = 5$ Kg of organic olives to obtain 1 Kg of organic olive oil, whereas only $R^n = 2.5$ Kg of olives are required to obtain 1 Kg of conventional olive oil.

There is a set of potential suppliers (farmers) $S$ indexed by $s$. We let $S^o$ denote the subset of potential organic suppliers and $S^n$ the subset of potential conventional suppliers. Each potential location for the production plant (Tunisia, France, or Spain) gives access to a set of potential suppliers (farmers), but also imposes some purchasing restrictions as we explain hereafter. Tunisia and Spain are among the largest producers of olives in the world, and almost all olive oil producers in these countries rely only on national supply. To fit with these common practices, we assume that if the production plant is located in Tunisia or in Spain, then all the required quantity of organic and conventional olives is purchased from the same country of production. In case of France, however, the quantities of olives produced are very low, which imposes some procurement constraints that are presented and discussed below.

If the production facility is located in France (in our case, Department of Var, South-East region), we assume that a maximum of 323.5 tons of organic olives can be procured from local suppliers (i.e., from the same department), 647 tons from regional suppliers (i.e., from the same region, including the quantity procured from local suppliers), and that the producer can buy any quantity from Spain. For conventional olives, a maximum of 1,219.5 tons can be procured from local suppliers, 2,439 tons from regional suppliers (including the quantity procured from local suppliers), and no quantity constraints if buying from Spain. Of course, it is challenging to get an accurate estimation of these procurement constraints as some big French producers have their own olive farms close to their production facilities, whereas other producers rely only on Spanish suppliers. We now explain how we obtained the above values. We recall that the highest base demand for the organic olive oil is $d_1^o = D_b^o(1 + \beta_1)$ = 258.75 tons. Given the rate $R^o = 5$, the required quantity of organic olives is approximately 1,294 tons. Similarly, the quantity of conventional olives required to produce the highest base demand for the conventional olive oil is 4,878 tons. We take these quantities (i.e., 1,294 tons for organic olives and 4,878 tons for conventional olives) as a reference to determine threshold values for supply constraints if the production is in France. Based on the data provided by French producers that we have interviewed, we assume for each variety that only 25% of the required quantity can be procured locally (i.e., up to 323.5 tons for organic olives and up to 1,219.5 tons for conventional olives), and only 50% can be procured regionally (i.e., up to 647 tons for organic olives and up to 2,439 tons for conventional olives). The olives' procurement from other regions in France is not possible in our case since most of French olives are produced in the South-East region. Table 3 recapitulates the olives supply constraints.

*Table 3. Olives' procurement constraints per production location*

<table>
<tr><th></th><th colspan="2">Production in France</th><th colspan="2">Production in Spain</th><th colspan="2">Production in Tunisia</th></tr>
<tr><th>Product variety</th><th>Organic</th><th>Conventional</th><th>Organic</th><th>Conven-tional</th><th>Organic</th><th>Conven-tional</th></tr>
<tr><td>Local procurement</td><td>Up to 323.5 tons</td><td>Up to 1,219.5 tons</td><td rowspan="3">All required olives from Spain</td><td rowspan="3">All required olives from Spain</td><td rowspan="3">All required olives from Tunisia</td><td rowspan="3">All required olives from Tunisia</td></tr>
<tr><td>Regional procurement</td><td>Up to 647 tons (including the local procurement)</td><td>Up to 2,439 tons (including the local procurement)</td></tr>
<tr><td>Other procurement options</td><td>Any required quantity can be purchased from Spain</td><td>Any required quantity can be purchased from Spain</td></tr>
</table>

The purchasing cost of organic olives (respectively, conventional olives) by facility $j$ from supply zone $s$ is denoted by $v_{sj}^{o}$ (respectively, $v_{sj}^{n}$). We obtained the average cost of conventional olives (transportation not included) from the data available at the International Olive Council (IOC 2015). As for the organic olives, we did not find reliable data in the literature, but our industrial partners argue that the cost is 25% higher. We present in Table 4 the cost of olives at farms in each supply zone (transportation not included). Clearly, we then add the transportation cost in function of the production facility location.

*Table 4. Olives' cost*

| | Conventional olives from | | | Organic olives from | | |
|---|---|---|---|---|---|---|
| | France | Spain | Tunisia | France | Spain | Tunisia |
| Olives' cost (€/Kg) | 0.8 | 0.68 | 0.54 | 1 | 0.85 | 0.675 |

Finally, it is important to note that we may have a different SC proximity level for each olive oil variety (e.g., a local SC for the organic variety and a national SC for the conventional variety).

## 4. The model

This section presents the model formulation. We first introduce the notation used for the parameters and decision variables (some notations were given in the previous section but will be recalled here).

*Demand and prices:*

- $D_b^o$: base demand for the organic olive oil,
- $D_b^n$: base demand for the conventional olive oil,
- $p_b^o$: base price of the organic olive oil,
- $p_b^n$: base price of the conventional olive oil,
- $p_u^o$: upper bound on the price of the organic olive oil,
- $p_u^n$: upper bound on the price of the conventional olive oil.

*Supply chain proximity level:*

- $I = \{1,2,3,4,5\}$: set of SC proximity indices, where 1 → local, 2 → regional, 3 → national, 4 → European, and 5 → international,
- $\beta_i^o$: percentage of gain in the base demand for the organic olive oil variety with SC proximity level $i \in I$ ($\beta_1^o \geq \beta_2^o \geq \beta_3^o \geq \beta_4^o \geq \beta_5^o = 0$),
- $\beta_i^n$: percentage of gain in the base demand for the conventional olive oil variety with SC proximity level $i \in I$ ($\beta_1^n \geq \beta_2^n \geq \beta_3^n \geq \beta_4^n \geq \beta_5^n = 0$),

*Production Facilities:*

- $J$: set of all potential locations for the olive oil production plant,

- $J_1 \subseteq J$: set of potential local locations (i.e., in the same department as the demand zone),
- $J_2 \subseteq J$: set of potential regional locations (i.e., in the same region as the demand zone, including the local locations),
- $J_4 \subseteq J$: set of potential European locations,
- $J_5 \subseteq J$: set of potential international locations.
- $m_j$: production cost at facility $j \in J$ per Kg of olive oil,
- $h_j$: distribution cost from facility $j \in J$ to the retailer per Kg of olive oil,
- $F_j$: Annual amortized opening cost of facility $j \in J$,

*Olive oil extraction machines:*

- $T$: set of potential extraction (mill) machines,
- $Q^t$: capacity of machine $t \in T$ per season (in terms of processed quantity of olives),
- $\tau^t$: annual amortized acquisition cost of one unit of machine $t \in T$,
- $R^o$: quantity of organic olives required to obtain one Kg of organic olive oil,
- $R^n$: quantity of conventional olives required to obtain one Kg of conventional olive oil.

*Suppliers:*

- $S^o$ ($S^n$): set of potential organic (conventional) suppliers or supply zones,
- $S_1^o \subseteq S^o$: set of potential local organic suppliers (i.e., in the same department as the demand zone),
- $S_1^n \subseteq S^n$: set of potential local conventional suppliers (i.e., in the same department as the demand zone),
- $S_2^o \subseteq S^o$: set of potential regional organic suppliers (i.e., in the same region as the demand zone, including the local suppliers),
- $S_2^n \subseteq S^n$: set of potential regional conventional suppliers (i.e., in the same region as the demand zone, including the local suppliers),
- $K_{sj}^o$: capacity of supply zone $s \in S^o$ associated with production facility $j \in J$,
- $K_{sj}^n$: capacity of supply zone $s \in S^n$ associated with production facility $j \in J$,
- $v_{sj}^o$: purchasing cost per Kg of organic olives by facility $j \in J$ from supply zone $s \in S^o$,

- $v_{sj}^{n}$: purchasing cost per Kg of conventional olives by facility $j \in J$ from supply zone $s \in S^{n}$.

*Decision variables:*

- $y_j \in \{0,1\}$: equals 1 if the olive oil production facility $j \in J$ is selected; 0 otherwise,
- $z_i^{o} \in \{0,1\}$: equals 1 if a SC with proximity level $i \in I$ is implemented for the organic variety; 0 otherwise,
- $z_i^{n} \in \{0,1\}$: equals 1 if a SC with proximity level $i \in I$ is implemented for the conventional variety; 0 otherwise,
- $w_{sj}^{o} \in \{0,1\}$: equals 1 if the organic supplier $s \in S^{o}$ supplies facility $j \in J$; 0 otherwise,
- $w_{sj}^{n} \in \{0,1\}$: equals 1 if the conventional supplier $s \in S^{n}$ supplies facility $j \in J$; 0 otherwise,
- $p^{o} \in \mathbb{R}^{+}$: selling price of the organic olive oil (per Kg),
- $p^{n} \in \mathbb{R}^{+}$: selling price of the conventional olive oil (per Kg),
- $x_j^{o} \in \mathbb{R}^{+}$: quantity of the organic olive oil produced in facility $j \in J$,
- $x_j^{n} \in \mathbb{R}^{+}$: quantity of the conventional olive oil produced in facility $j \in J$,
- $q_{sj}^{o} \in \mathbb{R}^{+}$: quantity of the organic olives purchased by facility $j \in J$ from supplier $s \in S^{o}$,
- $q_{sj}^{n} \in \mathbb{R}^{+}$: quantity of the conventional olives purchased by facility $j \in J$ from supplier $s \in S^{n}$,
- $\mu^{t} \in \mathbb{N}$: number of machines of type $t \in T$ installed in the selected production facility.

Using the above notation, we formulate the model as follows.

$$\begin{aligned} \operatorname{Max} \Pi = \sum_{j \in J} \left( \left(p^{o} - m_j - h_j\right) x_j^{o} + \left(p^{n} - m_j - h_j\right) x_j^{n} \right) - \sum_{j \in J} F_j y_j - \sum_{t \in T} Q^{t} \mu^{t} \\ - \sum_{j \in J} \left( \sum_{s \in S^{o}} v_{sj}^{o} q_{sj}^{o} + \sum_{s \in S^{n}} v_{sj}^{n} q_{sj}^{n} \right) \end{aligned} \tag{3}$$

Subject to,

$$\sum_{j \in J} y_j \leq 1 \tag{4}$$

$$x_j^{o} \leq \Psi y_j \quad \forall j \in J \tag{5}$$

$$x_j^{n} \leq \Psi y_j \quad \forall j \in J \tag{6}$$

$$\sum_{i \in I} z_i^{o} = \sum_{i \in I} z_i^{n} = 1 \tag{7}$$

$$\sum_{j\in J} x_j^o \le D_b^o\left(1+\sum_{i\in I}\beta_i^o z_i^o\right) - \alpha^o(p^o - p_b^o) \tag{8}$$

$$\sum_{j\in J} x_j^n \le D_b^n\left(1+\sum_{i\in I}\beta_i^n z_i^n\right) - \alpha^n(p^n - p_b^n) \tag{9}$$

$$\sum_{j\in J_5} y_j = z_5^o = z_5^n \tag{10}$$

$$\sum_{j\in J_4} y_j = z_4^o = z_4^n \tag{11}$$

$$z_1^o \le \sum_{j\in J_1} y_j \tag{12}$$

$$\sum_{s\in S^o \setminus S_1^o} w_{sj}^o \le \Psi(1 - z_1^o) \quad \forall j \in J_1 \tag{13}$$

$$z_2^o \le \sum_{j\in J_2} y_j \tag{14}$$

$$\sum_{s\in S^o \setminus S_2^o} w_{sj}^o \le \Psi(1 - z_2^o) \quad \forall j \in J_2 \tag{15}$$

$$z_1^n \le \sum_{j\in J_1} y_j \tag{16}$$

$$\sum_{s\in S^n \setminus S_1^n} w_{sj}^n \le \Psi(1 - z_1^n) \quad \forall j \in J_1 \tag{17}$$

$$z_2^n \le \sum_{j\in J_2\cup J_1} y_j \tag{18}$$

$$\sum_{s\in S^n \setminus S_2^n} w_{sj}^n \le \Psi(1 - z_2^n) \quad \forall j \in J_2 \tag{19}$$

$$w_{sj}^o \le y_j \quad \forall s \in S^o, \forall j \in J \tag{20}$$

$$w_{sj}^n \le y_j \quad \forall s \in S^n, \forall j \in J \tag{21}$$

$$\sum_{s\in S^o} q_{sj}^o \ge R^o x_j^o \quad \forall j \in J \tag{22}$$

$$\sum_{s\in S^n} q_{sj}^n \ge R^n x_j^n \quad \forall j \in J \tag{23}$$

$$q_{sj}^o \le K_{sj}^o w_{sj}^o \quad \forall s \in S^o, \forall j \in J \tag{24}$$

$$q_{sj}^n \le K_{sj}^n w_{sj}^n \quad \forall s \in S^n, \forall j \in J \tag{25}$$

$$\sum_{j\in J} R^o x_j^o + R^n x_j^n \le \sum_{t\in T} Q^t \mu^t \tag{26}$$

$$p_b^o \le p^o \le p_u^o \tag{27}$$

$$p_b^n \le p^n \le p_u^n \tag{28}$$

Objective function (3) maximizes the profit, which is equal to the revenues generated from the organic and conventional olive oils minus the different costs of production, distribution, purchasing, production plant opening, and mill machines acquisition. Constraint (4) imposes that at most only one facility can be selected. Using a sufficiently big number, denoted by $\Psi$, constraints (5) and (6) guarantee for the organic and conventional varieties, respectively, that the olive oil production occurs only in an open facility.

For each olive oil variety, constraint (7) imposes that exactly one SC proximity level is selected. We recall that the SC proximity level of the organic variety may be different from that of the conventional variety and, thus, it is possible to have $z_i^o \neq z_i^n$. Constraint (8) imposes that the produced quantity of the organic olive oil cannot exceed the demand for this variety. We recall that the demand for the organic variety offered at price $p^o$ and a SC proximity level $i$ is given in equation (1). In the model, the SC proximity level is a decision variable (determined by $z_i^o$ for the organic olive oil). The price is also a decision variable ($p^o$ for the organic olive oil). Thus, the demand for the organic variety is given by $D_b^o(1 + \sum_{i \in I} \beta_i^o z_i^o) - \alpha^o(p^o - p_b^o)$. With the same approach, we impose in constraint (9) that the produced quantity of the conventional olive oil cannot exceed the demand for this variety.

Constraint (10) imposes that we have an international SC for both varieties if and only if the olive oil production facility is located outside Europe (as explained in Section 3). Constraint (11) imposes that we have a European SC for both varieties if and only if the production facility is located in Europe (excluding the country of the demand). If the SC is neither international nor European, then the selected production facility $j$ is in the same country as the demand zone, which means that we have at least a national SC. Constraint (12) imposes that if the SC of the organic variety is local (i.e., $z_1^o = 1$), then the selected production facility must be local (i.e., $\sum_{j \in J_1} y_j = 1$). In addition, constraint (13) imposes that a local SC for the organic variety requires that all the organic suppliers must be local, which means that the non-local suppliers must not be selected (i.e., $\sum_{s \in S^o \setminus S_1^o} w_{sj}^o = 0 \ \forall j \in J_1$). Constraint (14) imposes that if the SC of the organic variety is regional (i.e., $z_2^o = 1$), then the selected production facility must be at least regional (i.e., $\sum_{j \in J_2} y_j = 1$). In addition, constraint (15) imposes that a regional SC for the organic variety requires that all the organic suppliers must be at least regional, which means that the non-regional suppliers must not be selected (i.e., $\sum_{s \in S^o \setminus S_2^o} w_{sj}^o = 0 \ \forall j \in J_2$). Similarly, constraints (16), (17), (18) and (19) are relative to the local and regional SCs for the conventional variety. The combination of the constraints imposed for the international, European, local and regional SCs guarantee that a national SC will be selected for a given variety if the production is made in the same country as the demand but the conditions for the local or the regional SCs are not satisfied (as explained in Section 3). Constraint (20) (respectively, Constraint (21)) guarantees that the allocation of an organic supplier (respectively, a conventional supplier) to a given facility can be made only when this facility is selected.

Constraint (22) (respectively, Constraint (23)) imposes that the total purchased quantity of organic olives (respectively, conventional olives) must not be smaller than the quantity $R^o x_j^o$ (respectively, $R^n x_j^n$) required to obtain the organic olive oil (respectively, the conventional olive oil). Constraint (24) adds the procurement constraints relative to the organic variety for each facility from each supply zone, and sets the value of $w_{sj}^o$ to 1 if supplier $s$ provides facility $j$ with organic olives. Similarly, we impose the procurement conditions relative to the conventional variety in constraint (25). Constraint (26) ensures that the total processed quantity of olives (i.e., $\sum_{j\in J} R^o x_j^o + R^n x_j^n$) does not exceed the total installed capacity (i.e., $\sum_{t\in T} Q^t \mu^t$). Finally, constraints (27) and (28) impose the lower and upper bounds on the prices for the organic and conventional varieties, respectively.

Our model assumed that the firm targets a specific market to fit with the practical problem faced by our industrial partners. This also has the advantage of clearly presenting and discussing the impact of the SC proximity levels. The model can be generalized to account for different markets by considering a specific demand function for each market ($D_b^{or}$ for the base organic demand in market $r$ and $D_b^{nr}$ for the base conventional demand in market $r$ instead of $D_b^o$ and $D_b^n$, respectively). In this case, the firm still offers one single product for each variety, but the product may have one proximity level for one market and another proximity level product for another market. Therefore, the proximity level variable will depend on the market (i.e., $z_i^{or}$ and $z_i^{nr}$ instead of $z_i^o$ and $z_i^n$, respectively). For instance, if the production is implemented in Spain and the firm targets both French and Spanish markets, then the product may be a local product in Spain and a European product in France. The prices will also depend on the market ($p^{or}$ and $p^{nr}$ instead of $p^o$ and $p^n$, respectively).

Finally, note that the proposed model has $4N_J N_S + 3N_J + N_T + 12$ variables (including $2N_J N_S + N_J + 10$ binary variables and $N_T$ integer variables) and $4N_J N_S + 8N_J + 18$ constraints, where $N_J$ is the number of potential facilities, $N_S$ is the number of potential supply zones, and $N_T$ in the number of potential extraction machines.

## 5. Solving approach

The proposed model is non-linear due to the multiplication of the price by the production quantity in the objective function. In its current form, our model cannot be solved with commercial optimization softwares, like Cplex, due to the non-linearity of the objective function. Moreover, the use of non-linear solvers is not an interesting option since these solvers often have a weak performance when there are many constraints in the model. In this section, we linearize the original model and show that the obtained model can be effectively solved to optimality with Cplex in a very small time. In practice, the olive oil prices are expressed in € with a maximum of two decimals. Hence, if we express the prices and costs of our model in cents, then we can consider prices ($p^o$ and $p^n$) as integer variables without losing optimality. In addition, the produced quantities can be rounded and expressed as integer variables without any optimality loss in practice. In this case, the non-linearity of the objective function becomes of the type of multiplication of two integer variables. We explain below how we linearize the product $p^o\, x_j^o$ in the objective function. The same methodology is applied to linearize $p^n\, x_j^n$ (but is not presented here to avoid redundancy).

The linearization of the product of two integer variables requires the representation of each original integer variable in a binary format (see, for instance, Glover 1975, Billionnet et al. 2012). The number of required binary variables depends on the upper bound of the integer variable. In practice, prices and quantities are finite, and there are upper bounds for both of them. The price upper bound can be considered as the highest price observed in the market, and the quantity upper bound is the highest possible amount of demand. To illustrate how we represent an integer variable in a binary format, we consider the following example. Assume the organic price upper bound is equal to 20. In this case, 5 binary variables are needed to represent all possible prices between 0 and 20. We denote these binary variables by $\rho_1^o, \rho_{2,}^o \dots, \rho_5^o$. We can see, for example, that $p^o = 19$ can be written as $\sum_{k=1}^{5}\left(2^{k-1}\right)\rho_k^o$ where

$\rho_1^o = 1, \rho_2^o = 1, \rho_3^o = 0, \rho_4^o = 0, \rho_5^o = 1$, and $p^o = 10$ can be written as $\sum_{k=1}^{5}(2^{k-1})\rho_k^o$ where $\rho_1^o = 0, \rho_2^o = 1, \rho_3^o = 0, \rho_4^o = 1, \rho_5^o = 0$. Note that $p^o$ is now in cents and, thus, its upper bound is much higher than 20. Therefore, we need a larger number of binary variables to obtain a binary representation of $p^o$, but the methodology is similar to the above example. With the same approach, we also represent $x_j^o$ in a binary format. After the binary representation of the integer variables, $p^o\, x_j^o$ is expressed as a sum of products of two binary variables. The product of two binary variables can be linearized using an auxiliary binary variable as we shall explain below. We now move to the general case. We use the following notation:

- $A$: maximum number of binary variables required for the representation of the organic price (indexed by *a*),
- $L$: maximum number of binary variables required for the representation of the organic olive oil quantity (indexed by *l*),
- $\rho_a^o$: binary variables used for the binary representation of $p^o$,
- $g_{lj}^o$: binary variables used for the binary representation of $x_j^o$,
- $\sigma_{alj}^o$: auxiliary binary variable ($\sigma_{alj}^o = g_{lj}^o \rho_a^o$).

To linearize $p^o x_j^o$, we add the following constraints to the model. Constraints (29) and (30) respectively represent the integer variables $p^o$ and $x_j^o$ in a binary format. Constraints (31), (32), and (33) guarantee that $\sigma_{alj}^o = g_{lj}^o \rho_a^o$. With these new constraints, we have $p^o x_j^o = \sum_{a=1}^{A}\sum_{l=1}^{L}(2^{a-1})(2^{l-1})\sigma_{alj}^o$. We finally replace $p^o x_j^o$ with $\sum_{a=1}^{A}\sum_{l=1}^{L}(2^{a-1})(2^{l-1})\sigma_{alj}^o$ in the objective function. We recall that we use the same approach to linearize $p^n\, x_j^n$.

$$p^o = \sum_{a=1}^{A}(2^{a-1})\rho_a^o \tag{29}$$

$$x_j^o = \sum_{l=1}^{L}(2^{l-1})g_{lj}^o \quad \forall j \in J \tag{30}$$

$$\sigma_{alj}^o \le g_{lj}^o \quad \forall a \in [1, \dots, A], l \in [1, \dots, L], j \in J \tag{31}$$

$$\sigma_{alj}^o \le \rho_a^o \quad \forall a \in [1, \dots, A], l \in [1, \dots, L], j \in J \tag{32}$$

$$\sigma_{alj}^{o} \geq g_{lj}^{o} + \rho_a^{o} - 1 \quad \forall a \in [1, \dots, A], l \in [1, \dots, L], j \in J \tag{33}$$

The model is now linear but uses a large number of binary variables. In total, $2\big(A + (A+1)LN_J\big)$ new binary variables are required, where $N_J$ is the number of potential facilities, $A$ is the number of binary variables required to represent the price and $L$ is the number of binary variables required to represent the production quantity. The linearization process also requires $2\big(AN_J(L+1) + N_J + 1\big)$ new constraints. The linearized model can be solved with Cplex. The current version of Cplex can effectively handle several thousands of variables and constraints. In the case of Mixed-Integer Programming models, the main computational issue is related to the memory required for the storage of the active nodes in the branch and bound tree (IBM Support). Therefore, the problem size does not provide a full estimation of the memory usage. Hence, it is worthy to assess the computational performance to guarantee that the model can be effectively used in practice. We define different model classes by varying the number of potential locations, which is the main factor that determines the size of the problem. For each class, we randomly generate 30 instances as follows. We allow the parameters to vary (increase or decrease) by a maximum of 20% from their base values. We solve each instance to optimality with Cplex. Table 5 provides the average computational time for each class. We evaluate the execution time with two different hardware architectures: (1) a dual-core laptop with a frequency of 2.4 GHz (for each core) and 8 Gb RAM, and (2) an 18-core workstation with a frequency of 2.4 GHz (for each core) and 256 Gb RAM. To see whether we can obtain a better computational performance with other solving techniques, we also solved the model using the reformulation-linearization technique proposed by Sherali and Alameddine (1992) for our numerical examples. Table 5 shows that the model can be solved to optimality with the adopted Bit-Linearization technique in less than one minute even with 9 potential locations. As shown in Table 5, we obtained slightly shorter computational times with the reformulation-linearization technique, but the difference is insignificant in practice.

*Table 5. Computational performance*

| Number of Potential Facilities | Average Execution Time (second) | | |
|---|---|---|---|
| | Bit-Linearization | | Reformulation-linearization, Sherali and Alameddine (1992) |
| | Laptop | WorkStation | WorkStation |

| | | | |
|---|---|---|---|
| 3 | 12.30 | 1.47 | 0.84 |
| 4 | 15.37 | 2.84 | 1.02 |
| 5 | 20.41 | 5.16 | 3.65 |
| 6 | 27.07 | 4.95 | 3.95 |
| 7 | 32.61 | 7.55 | 5.89 |
| 8 | 32.48 | 7.83 | 6.01 |
| 9 | 42.91 | 8.92 | 6.98 |

## 6. Numerical experiments and managerial insights

In this section, we perform numerical experiments to investigate the interplay of consumers' sensitivity to the SC proximity level, the mix of organic and conventional varieties, the price, the demand, and the profit. We discuss managerial insights and provide the olive oil producers with decision-aid tools.

### 6.1. Impact of consumers' sensitivity to SC proximity level

To investigate the effect of the consumers' sensitivity to the SC proximity level, we consider the base scenario described in Section 3 and vary the value of $\beta = [\beta_1, \beta_2, \beta_3, \beta_4, \beta_5]$. Thus, we increase $\beta_1$ from 0 to 75 with a step of 5 and, similar to our base scenario (in which $\beta = [25,20,15,5,0]$), we always consider $\beta_2 = \frac{4\beta_1}{5}$, $\beta_3 = \frac{3\beta_1}{5}$, and $\beta_4 = \frac{\beta_1}{5}$ in order to keep the same tendency. We recall that we always have, by definition, $\beta_5 = 0$. We solve the model to optimality and present the results in Table 6.

*Table 6. Impact of consumers' sensitivity to SC proximity*

| $\beta$ | SC classification | | Production quantity (Kg) | | Price (€) | | Profit |
|---|---|---|---|---|---|---|---|
| | Organic | Conventional | Organic | Conventional | Organic | Conventional | |
| [0,0,0,0,0] | International | International | 140,383 | 1,088,500 | 13.14 | 8.95 | 9,373,998 |
| [5,4,3,1,0] | International | International | 139,650 | 1,090,000 | 13.19 | 8.94 | 9,374,226 |
| [10,8,6,2,0] | International | International | 140,250 | 1,088,495 | 13.15 | 8.95 | 9,374,088 |
| [15,12,9,3,0] | Regional | Regional | 129,374 | 975,623 | 15.53 | 10.95 | 9,608,935 |
| [20,16,12,4,0] | Regional | Regional | 129,270 | 975,260 | 16.09 | 11.37 | 10,086,741 |
| [25,20,15,5,0] | Regional | Regional | 129,300 | 974,700 | 16.64 | 11.79 | 10,562,485 |
| [30,24,18,6,0] | Regional | Regional | 129,330 | 975,623 | 17.19 | 12.20 | 11,042,702 |
| [35,28,21,7,0] | Regional | Regional | 129,360 | 975,080 | 17.74 | 12.62 | 11,518,375 |
| [40,32,24,8,0] | Regional | Regional | 129,375 | 975,625 | 18.29 | 13.03 | 11,995,338 |
| [45,36,27,9,0] | Regional | Regional | 129,375 | 975,459 | 18.84 | 13.45 | 12,474,409 |
| [50,40,30,10,0] | Regional | Regional | 129,300 | 974,899 | 19.4 | 13.87 | 12,949,027 |
| [55,44,33,11,0] | Regional | Regional | 129,330 | 975,625 | 19.95 | 14.28 | 13,428,973 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| [60,48,36,12,0] | Regional | Regional | 129,375 | 975,280 | 20.00 | 14.70 | 13,841,591 |
| [65,52,39,13,0] | National | Regional | 169,080 | 975,625 | 16.61 | 15.00 | 14,148,238 |
| [70,56,42,14,0] | National | National | 172,290 | 1,369,120 | 16.81 | 11.45 | 14,330,478 |
| [75,60,45,15,0] | National | National | 175,500 | 1,393,447 | 17.01 | 11.60 | 14,833,583 |

Different interesting results can be deduced from Table 6. We first investigate how the consideration of the consumers' sensitivity to the SC proximity changes the olive oil SC decisions. For this purpose, we compare the case where the consumers' sensitivity to the SC proximity is considered (i.e., $\beta$>0) to the case where this sensitivity is ignored by the managers (i.e., $\beta$=0). For instance, while comparing the results for $\beta = [0,0,0,0,0]$ to those obtained in our base case study (i.e., for $\beta = [25,20,15,5,0]$), we see that the consideration of the consumers' sensitivity to the SC proximity leads to moving from an international SC to a regional SC for both varieties. Although implementing a more local SC incurs a higher cost in this case, this cost increase is offset by the additional revenues resulting from quoting higher prices for both varieties (16.64 vs. 13.14 for the organic variety, and 11.79 vs. 8.95 for the conventional variety). Note that the higher prices offered with $\beta = [25,20,15,5,0]$ do not lead to a significant decrease in the effective demand (129,300 vs. 140,388 for the organic variety, and 974,700 vs. 1,088,500 for the conventional variety) since a regional SC generates a much higher base demand than an international SC (see Eqs. (1) and (2)). Therefore, the producer capitalizes on the base demand increase (resulting from offering more local products) by increasing the prices, which finally leads to a higher profit (10,562,485 vs. 9,373,998).

To quantify the gain resulting from considering the demand sensitivity to the SC proximity (instead of ignoring it), we compare the optimal profit obtained with our model for each given $\beta$ (profit denoted by $\pi$) with the profit that would be obtained if the firm ignores the demand sensitivity to the SC proximity and, thus, designs the SC while assuming $\beta = [0,0,0,0,0]$ (profit denoted by $\pi_0$). To perform this comparison, we proceed as follows. For each value of $\beta$ in Table 6, we do the following:

- We solve the model with the right value of $\beta$ and obtain the optimal profit $\pi$.
- We solve the model again with $\beta = [0,0,0,0,0]$. We denote by *Sol[0]* the strategic decisions in this case (i.e., the decisions of facility location, supply zone selection, SC proximity level, and production capacity). This SC configuration (obtained with $\beta = [0,0,0,0,0]$) will lead to a different base demand since the market is indeed sensitive to the SC proximity, although this is ignored by the

firm. We take the strategic decisions given by *Sol[0]* and do not change them. We then solve the model again with the right value of $\beta$ to determine the optimal prices and quantities that would be decided by the producer after observing the real base demand (given by the real value of $\beta$) but with the strategic decisions fixed to *Sol[0]* (since these decisions cannot be changed in practice). We calculate the optimal profit in this case and obtain profit $\pi_0$.

- We calculate the gain resulting from considering the market sensitivity to the SC proximity as follows: $Gain = \frac{\pi - \pi_0}{\pi_0} \times 100\%$.

We find that designing the olive oil SC while considering the market sensitivity to the SC proximity leads to an average gain of 29.21%. This significant gain shows the practical interest of our modeling approach. The main ideas discussed above are highlighted in Observation 1.

***Observation 1.*** *Considering the market sensitivity to the SC proximity leads the producer to switching from an international SC to more local SC configurations and, thus, to offering more local products.*

*Designing the SC while ignoring the market sensitivity to the SC proximity can prevent the producer from realizing much higher profits.*

We now focus on the effect of increasing the market sensitivity to the SC proximity (i.e., increasing $\beta = [\beta_1, \beta_2, \beta_3, \beta_4, \beta_5]$). We recall that we always have $\beta_2 = \frac{4\beta_1}{5}$, $\beta_3 = \frac{3\beta_1}{5}$, $\beta_4 = \frac{\beta_1}{5}$, and $\beta_5 = 0$. We also recall that the demand for the organic variety with SC proximity level $i$ is $d_i^o = D_b^o(1 + \beta_i) - \alpha^o\ (p^o - p_b^o)\ \ \forall\ i = \{1, 2, \dots, 5\}$ (we have a similar function for the conventional variety). Therefore, an increase in the consumers' sensitivity to the SC proximity means that the producer will observe a higher base demand (i.e., larger values for $D_b^o(1 + \beta_i)$ and $D_b^n(1 + \beta_i)$) if and only if the implemented SC is more local than an international SC. In case of an international SC, an increase in the consumers' sensitivity to the SC proximity has no impact on the demand. Note also that a higher base demand does not necessarily mean more sales since, on the one hand, the effective demand decreases in price and, on the other hand, it is not always possible to match production with demand because of the olives supply constraints.

It is expected that an increase in $\beta$ leads the producer to implementing a more local SC. In Table 6, this happens for instance when $\beta$ increases from [10,8,6,2,0] to [15,12,9,3,0]. In this case, the model switches from an international SC to a regional SC for both organic and conventional varieties. However, we observe that a higher $\beta$ may also lead to a more global SC configuration, which is less intuitive. For instance, an increase in $\beta$ from [60, 48, 36, 12, 0] to [65, 52, 39, 13, 0] implies switching from a regional SC to a national SC for the organic variety. This unexpected situation requires more investigation. Indeed, when $\beta$ increases, the firm should either produce more or/and increase the price to benefit from this market growth. Producing more requires purchasing more, which is not always possible without changing the supply zone (and, therefore, without changing the SC proximity level) given the relatively small quantity of organic olives available near the production facility in France. This explains why the model moves from a regional to a national SC. In fact, opting for a national SC (instead of a regional SC) for the organic variety gives access to larger quantities of olives and, therefore, increases the organic production from 129,375 to 169,080 (see Table 6). When $\beta$ increases, it may also be possible to capitalize more on pricing and, thus, increase the price instead of increasing the production. This occurs when the price increase is more profitable or when the demand increase is not possible due to supply constraints. However, the profit is concave in price and, thus, after a threshold price value, increasing the price will incur less profit. This explains why the model reduces the organic price when $\beta$ increases from [60, 48, 36, 12, 0] to [65, 52, 39, 13, 0]. Based on this analysis, we highlight the main result in Observation 2.

***Observation 2.*** *An increase in consumers' preference to more local SCs may lead the producer to implementing a more global SC due to the limited quantity of olives available.*

We continue the analysis of Table 6. We now focus on the differences between both olive oil varieties. Since the organic variety is more premium and targets less price-sensitive consumers, it is usual in practice to dedicate the more local SC exclusively to the organic variety while offering the conventional olive oil variety with a more global SC. This corresponds to what we observed in the French olive oil market. However, we see for $\beta$ =[65, 52, 39, 13, 0] that the organic variety is obtained with a national SC, whereas the conventional variety is obtained with a regional SC. Hence, unlike our expectation, it is the conventional variety that benefits from a more local SC and not the organic variety. The reason is the following. For the conventional variety, the quoted price is relatively low. Hence, when $\beta$ increases, the firm can improve the profit by increasing the price while keeping the same production amount. Since the produced quantity of olive oil does not change, the required quantity of olives can still be purchased from the same supply zone and, thus, the producer can still use a regional SC for the conventional variety. For the organic variety, the quoted price is relatively high. Hence, when $\beta$ increases, the firm should capitalize not only on the price (since a significant increase in price is no longer profitable) but also on increasing production and sales. However, an increase in the produced quantity means a higher requirement for organic olives. This requirement cannot be satisfied in France, which leads to buying the organic olives from Spain and, thus, relying on a national SC for the organic olive oil variety. This analysis leads to Observation 3.

***Observation 3.*** *The conventional variety may be produced with a more local SC than the organic variety.*

### 6.2. Impact of organic and conventional market size disparity

The global organic food market is expected to grow at a compound annual growth rate of 16.5% from 2021 and reach \$366.5 billion in 2023 (TBRC 2020). We then investigate the effect of the disparity in market size between the organic and conventional varieties. We aim to understand what happens if there are more organic consumers. To address this question, we first recall that the total base demand in our case study is $D_b = D_b^o + D_b^n = 1{,}768{,}000\ Kg$. We keep $D_b$ constant and increase $D_b^o$ from 20,700 to 1,324,800 with a step of 20,700 (we then decrease $D_b^n$ accordingly). The results are presented in Table 7 (due to its length, Table 7 is given in the Appendix).

We see in Table 7 that when the organic market size increases (i.e., $D_b^o$ increases from 20,700 to 1,324,800) and, therefore, the conventional market size decreases, the model generally opts for a more global SC. When the conventional market size increases and, therefore, the organic market size decreases, the model generally opts for a more local SC. In fact, for the organic variety, the international SC is first selected, and then the model switches to a European, a national, a regional and finally a local SC. This choice of a more local SC can be explained by the fact that a smaller base organic demand favors increasing the demand over reducing the cost. Therefore, when the base organic demand gets lower, a more local SC is selected. For the conventional variety, the international SC is first selected, and then the model switches to a European, a regional and finally a national SC. We have the same tendency as for the organic variety despite the last switching from a regional to a national SC for large sizes of the conventional market, which is explained by the supply constraints. We highlight the main result in Observation 4.

***Observation 4.*** *A greater conventional market or a smaller organic market can act as drivers for more local SC configurations.*

### 6.3. Impact of offering a mix of organic and conventional varieties

With the same pairs of $(D_b^o, D_b^n)$ considered in the previous subsection, we now compare three different strategies: (i) offering only the organic olive oil, (ii) offering only the conventional olive oil, and (iii) offering of mix of organic and conventional varieties as we do in our original model. When only one variety is targeted, we constraint the production quantity of the other variety to equal zero. The results are presented in Table 8 (given in the Appendix).

We observe that offering both varieties leads to a SC which is more local than (or, at least, with the same proximity level as) the SC obtained when only one variety is offered. This shows that the trade-offs that govern the optimal decisions in case of a mixed offer are different from those that guide the decisions when only one olive oil variety is offered to the consumers. For instance, in case of $D_b^o = 20{,}700$ and $D_b^n = 1{,}747{,}300$, we have an international SC (i.e., production in Tunisia) when only the organic variety is offered, and a national SC (i.e., production in France) when only the conventional variety is offered. However, when both varieties are offered, we must choose only one location for the production facility and, therefore, it is not possible to produce in both France and Tunisia. Since the base organic demand in this case is too small with comparison to the base conventional demand ($D_b^o = 20{,}700$ and $D_b^n = 1{,}747{,}300$), it is more profitable to favor the conventional product when both varieties are offered and, thus, to implement the production facility in France. In this case, the organic SC can be either local, regional or national. The model chooses here a local SC for the organic variety. The reason is the following. Given the high production cost in France, there is a need to increase the price or/and the demand. Since the price of the organic product cannot be too high (because the base organic demand is very small, and demand decreases in price), there is a need to increase the demand as mush as possible, which justifies the choice of the local SC for the organic product. The main result of the above discussion is highlighted in Observation 5.

***Observation 5.*** *Offering a mix of organic and conventional varieties instead of only one variety would lead to implementing a more local SC.*

## 7. Conclusion

The average world consumption of olive oil has almost doubled over the past 25 years and olive oil SCs are gaining interest in theory and practice. New trends in the agrifood market, in general, and the olive oil market, in particular, require adapting the SC for a better matching between supply and demand. In this study, we investigated how to design an olive oil SC while considering both organic and conventional market segments and accounting for the sensitivity of demand to price and SC proximity level. The proposed model has been developed with the collaboration of olive oil producers in the Mediterranean area. The model matches the real practices in the olive oil industry. We solved the model and performed numerical analyses to derive managerial insights.

Our results, obtained from the base case study and a set of sensitivity analyses, are relevant for practitioners. Some of these results are not intuitive. For instance, we show that an increase in the consumers' preference to more local SCs may lead the producer to implementing a more global SC due to the limited quantity of olives available locally. Furthermore, the organic (premium) olive oil variety may be produced with a more global SC than the conventional variety. We also show that a greater conventional market or a smaller organic market can act as drivers for more local SC configurations. Finally, offering a mix of organic and conventional varieties instead of only one variety would lead to implementing a more local SC.

Our modeling effort and analysis come with limitations that can provide directions for further research in the area. First, our managerial findings shed light on some interesting behaviors but are specific to the considered case study. The consideration of other data may lead to different insights. It is important to note that each agrifood product may have some specific features with respect to the availability of supply zones, the production process, and/or the demand characteristics. Therefore, the adjustment of our model is necessary before we can use it to address other situations or other products. Nevertheless, our model is a first step to understand the impact of new market trends in the agrifood sector, which are the rise of the organic market segment and the consumers' sensitivity to the SC proximity. We showed that the firm's optimal strategy depends on the availability of olives (olive farms) in each location. Therefore, it would be interesting to consider how the supply and availability of olives, in particular the organic olives, will evolve in the future as this will impact the SC design decisions. A dynamic version of the model (with time-dependent parameters and decisions) could be used to consider this issue. Future research can also consider supply uncertainties that result from uncertain olive production yield, which impacts the olives availability and the purchase price.

## Appendix

*Table 7. Impact of market size disparity*

| | | SC Classification | | Production (Kg) | | Price (€) | | Profit |
|---|---|---|---|---|---|---|---|---|
| $D_b^o$ | $D_b^n$ | Organic | Conventional | Organic | Conventional | Organic | Conventional | |
| 20700 | 1747300 | Local | National | 22275 | 1411395 | 8.79 | 8.79 | 9,070,620 |
| 41400 | 1726600 | Local | National | 49350 | 1393590 | 8.76 | 8.76 | 9,006,084 |
| 62100 | 1705900 | Regional | National | 70520 | 1361785 | 8.80 | 8.80 | 8,931,376 |
| 82800 | 1685200 | Regional | National | 94960 | 1335980 | 8.81 | 8.81 | 8,863,521 |
| 103500 | 1664500 | Regional | National | 118991 | 1308159 | 8.83 | 8.83 | 8,795,374 |
| 124200 | 1643800 | Regional | National | 129023 | 1296370 | 9.20 | 8.77 | 8,723,796 |
| 144900 | 1623100 | Regional | National | 129391 | 1282559 | 9.81 | 8.72 | 8,650,943 |
| 165600 | 1602400 | Regional | National | 129400 | 1268758 | 10.43 | 8.67 | 8,579,447 |
| 186300 | 1581700 | National | National | 168645 | 1234955 | 9.84 | 8.72 | 8,527,587 |
| 207000 | 1561000 | National | Regional | 174450 | 975200 | 10.29 | 10.29 | 8,507,761 |
| 227700 | 1540300 | National | Regional | 197455 | 974360 | 10.31 | 10.17 | 8,502,426 |
| 248400 | 1519600 | National | Regional | 196860 | 975519 | 10.92 | 10.04 | 8,501,823 |
| 269100 | 1498900 | National | Regional | 222265 | 974680 | 10.88 | 9.92 | 8,504,961 |
| 289800 | 1478200 | National | Regional | 234070 | 975600 | 11.18 | 9.79 | 8,520,982 |
| 310500 | 1457500 | National | Regional | 246274 | 975000 | 11.47 | 9.67 | 8,542,435 |
| 331200 | 1436800 | National | Regional | 258080 | 975600 | 11.77 | 9.54 | 8,570,048 |
| 351900 | 1416100 | National | Regional | 269883 | 975320 | 12.07 | 9.42 | 8,608,082 |
| 372600 | 1395400 | National | Regional | 282090 | 974480 | 12.36 | 9.30 | 8,649,384 |
| 393300 | 1374700 | National | Regional | 294695 | 975583 | 12.64 | 9.17 | 8,701,511 |
| 414000 | 1354000 | National | Regional | 298499 | 974800 | 13.14 | 9.05 | 8,756,266 |
| 434700 | 1333300 | National | Regional | 298305 | 975599 | 13.74 | 8.92 | 8,812,282 |
| 455400 | 1312600 | National | Regional | 329310 | 975119 | 13.56 | 8.80 | 8,883,086 |
| 476100 | 1291900 | National | Regional | 341515 | 974280 | 13.85 | 8.68 | 8,960,344 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 496800 | 1271200 | National | Regional | 351719 | 975440 | 14.19 | 8.55 | 9,047,539 |
| 517500 | 1250500 | National | Regional | 364725 | 974600 | 14.46 | 8.43 | 9,139,193 |
| 538200 | 1229800 | National | Regional | 378530 | 975600 | 14.71 | 8.30 | 9,239,285 |
| 558900 | 1209100 | National | Regional | 388735 | 974920 | 15.05 | 8.18 | 9,346,223 |
| 579600 | 1188400 | National | Regional | 395340 | 974080 | 15.48 | 8.06 | 9,458,672 |
| 600300 | 1167700 | National | Regional | 395519 | 975231 | 16.07 | 7.93 | 9,573,675 |
| 621000 | 1147000 | National | Regional | 425343 | 974400 | 15.92 | 7.81 | 9,698,090 |
| 641700 | 1126300 | National | Regional | 435555 | 975559 | 16.26 | 7.68 | 9,833,968 |
| 662400 | 1105600 | National | Regional | 448160 | 974720 | 16.54 | 7.56 | 9,975,888 |
| 683100 | 1084900 | National | Regional | 461565 | 973879 | 16.80 | 7.44 | 10,125,027 |
| 703800 | 1064200 | National | Regional | 471370 | 975040 | 17.15 | 7.31 | 10,281,755 |
| 724500 | 1043500 | National | Regional | 483575 | 974200 | 17.44 | 7.19 | 10,445,283 |
| 745200 | 1022800 | National | Regional | 496580 | 959360 | 17.71 | 7.14 | 10,616,741 |
| 765900 | 1002100 | National | Regional | 507985 | 944520 | 18.02 | 7.09 | 10,796,770 |
| 786600 | 981400 | National | Regional | 516589 | 927680 | 18.40 | 7.05 | 10,984,911 |
| 807300 | 960700 | National | Regional | 523967 | 910840 | 18.81 | 7.01 | 11,180,154 |
| 828000 | 940000 | National | Regional | 524200 | 912000 | 19.40 | 6.88 | 11,379,456 |
| 848700 | 919300 | National | Regional | 524005 | 895160 | 20.00 | 6.84 | 11,578,517 |
| 869400 | 898600 | National | Regional | 524287 | 886320 | 20.00 | 6.76 | 11,471,794 |
| 890100 | 877900 | National | Regional | 524287 | 875480 | 20.00 | 6.69 | 11,362,381 |
| 910800 | 857200 | European | European | 517500 | 852060 | 19.67 | 6.04 | 11,428,226 |
| 931500 | 836500 | International | International | 517500 | 836495 | 19.05 | 5.80 | 11,508,179 |
| 952200 | 815800 | International | International | 517400 | 815800 | 19.57 | 5.80 | 11,686,688 |
| 972900 | 795100 | International | International | 517500 | 795099 | 20.00 | 5.80 | 11,821,801 |
| 993600 | 774400 | International | International | 517499 | 774400 | 20.00 | 5.80 | 11,732,779 |
| 1014300 | 753700 | International | International | 517499 | 753695 | 20.00 | 5.80 | 11,643,747 |
| 1035000 | 733000 | International | International | 517499 | 730998 | 20.00 | 5.81 | 11,564,260 |
| 1055700 | 712300 | International | International | 517500 | 712191 | 20.00 | 5.80 | 11,476,096 |
| 1076400 | 691600 | International | International | 517500 | 691599 | 20.00 | 5.80 | 11,387,551 |
| 1097100 | 670900 | International | International | 517500 | 670847 | 20.00 | 5.80 | 11,298,317 |
| 1117800 | 650200 | International | International | 517499 | 650200 | 20.00 | 5.80 | 11,209,519 |
| 1138500 | 629500 | International | International | 517500 | 629500 | 20.00 | 5.80 | 11,120,525 |
| 1159200 | 608800 | International | International | 517500 | 608767 | 20.00 | 5.80 | 11,031,373 |
| 1179900 | 588100 | International | International | 517500 | 588095 | 20.00 | 5.80 | 10,942,484 |
| 1200600 | 567400 | International | International | 517500 | 567400 | 20.00 | 5.80 | 10,853,495 |
| 1221300 | 546700 | International | International | 517500 | 546687 | 20.00 | 5.80 | 10,764,429 |
| 1242000 | 526000 | International | International | 517487 | 525951 | 20.00 | 5.80 | 10,685,824 |
| 1262700 | 505300 | International | International | 517499 | 505299 | 20.00 | 5.80 | 10,597,244 |
| 1283400 | 484600 | International | International | 517500 | 484479 | 20.00 | 5.80 | 10,507,735 |
| 1304100 | 463900 | International | International | 517500 | 463895 | 20.00 | 5.80 | 10,419,224 |
| 1324800 | 443200 | International | International | 517499 | 443135 | 20.00 | 5.80 | 10,329,939 |

*Table 8. Impact of offering a mix of organic and conventional varieties*

| | | Only Organic | | Only Conventional | | Both Varieties | | |
|---|---|---|---|---|---|---|---|---|
| $D_b^o$ | $D_b^n$ | SC Level | Profit | SC Level | Profit | Organic SC Level | Conventional SC Level | Profit |
| 20700 | 1747300 | International | 85,805 | National | 8,981,140 | Local | National | 9,070,620 |
| 41400 | 1726600 | International | 192,410 | National | 8,829,264 | Local | National | 9,006,084 |
| 62100 | 1705900 | International | 299,010 | National | 8,677,388 | Regional | National | 8,931,376 |
| 82800 | 1685200 | International | 405,620 | National | 8,532,312 | Regional | National | 8,863,521 |
| 103500 | 1664500 | International | 501,425 | National | 8,380,437 | Regional | National | 8,795,374 |
| 124200 | 1643800 | International | 607,984 | National | 8,228,561 | Regional | National | 8,723,796 |
| 144900 | 1623100 | International | 714,635 | National | 8,076,685 | Regional | National | 8,650,943 |
| 165600 | 1602400 | International | 821,240 | National | 7,925,026 | Regional | National | 8,579,447 |
| 186300 | 1581700 | International | 927,845 | National | 7,774,647 | National | National | 8,527,587 |
| 207000 | 1561000 | International | 1,030,674 | National | 7,625,685 | National | Regional | 8,507,761 |
| 227700 | 1540300 | International | 1,133,193 | National | 7,478,126 | National | Regional | 8,502,426 |
| 248400 | 1519600 | International | 1,248,026 | National | 7,332,009 | National | Regional | 8,501,823 |
| 269100 | 1498900 | International | 1,368,347 | National | 7,191,519 | National | Regional | 8,504,961 |
| 289800 | 1478200 | International | 1,493,918 | National | 7,051,912 | National | Regional | 8,520,982 |
| 310500 | 1457500 | International | 1,624,925 | National | 6,911,866 | National | Regional | 8,542,435 |
| 331200 | 1436800 | International | 1,761,248 | National | 6,772,442 | National | Regional | 8,570,048 |
| 351900 | 1416100 | International | 1,902,927 | National | 6,633,412 | National | Regional | 8,608,082 |
| 372600 | 1395400 | International | 2,049,962 | National | 6,495,783 | National | Regional | 8,649,384 |
| 393300 | 1374700 | International | 2,200,610 | National | 6,359,569 | National | Regional | 8,701,511 |
| 414000 | 1354000 | International | 2,353,296 | National | 6,224,773 | National | Regional | 8,756,266 |
| 434700 | 1333300 | International | 2,516,403 | Regional | 6,114,328 | National | Regional | 8,812,282 |
| 455400 | 1312600 | International | 2,684,862 | Regional | 6,114,322 | National | Regional | 8,883,086 |
| 476100 | 1291900 | International | 2,858,677 | Regional | 6,086,383 | National | Regional | 8,960,344 |
| 496800 | 1271200 | International | 3,037,848 | Regional | 5,966,487 | National | Regional | 9,047,539 |
| 517500 | 1250500 | National | 3,234,387 | Regional | 5,844,751 | National | Regional | 9,139,193 |
| 538200 | 1229800 | National | 3,455,250 | Regional | 5,724,088 | National | Regional | 9,239,285 |
| 558900 | 1209100 | National | 3,683,192 | Regional | 5,602,978 | National | Regional | 9,346,223 |
| 579600 | 1188400 | National | 3,916,484 | Regional | 5,481,208 | National | Regional | 9,458,672 |
| 600300 | 1167700 | National | 4,150,427 | Regional | 5,361,046 | National | Regional | 9,573,675 |
| 621000 | 1147000 | National | 4,398,721 | Regional | 5,239,099 | National | Regional | 9,698,090 |
| 641700 | 1126300 | National | 4,654,997 | Regional | 5,119,002 | National | Regional | 9,833,968 |
| 662400 | 1105600 | National | 4,918,358 | Regional | 4,997,533 | National | Regional | 9,975,888 |
| 683100 | 1084900 | National | 5,188,739 | Regional | 4,875,974 | National | Regional | 10,125,027 |
| 703800 | 1064200 | National | 5,466,328 | Regional | 4,755,445 | National | Regional | 10,281,755 |
| 724500 | 1043500 | National | 5,750,938 | Regional | 4,634,336 | National | Regional | 10,445,283 |
| 745200 | 1022800 | National | 6,041,671 | Regional | 4,514,142 | National | Regional | 10,616,741 |
| 765900 | 1002100 | National | 6,333,303 | Regional | 4,395,470 | National | Regional | 10,796,770 |
| 786600 | 981400 | National | 6,636,470 | Regional | 4,278,342 | National | Regional | 10,984,911 |
| 807300 | 960700 | National | 6,947,893 | Regional | 4,162,474 | National | Regional | 11,180,154 |
| 828000 | 940000 | National | 7,259,936 | Regional | 4,048,720 | National | Regional | 11,379,456 |
| 848700 | 919300 | National | 7,571,593 | Regional | 3,936,208 | National | Regional | 11,578,517 |
| 869400 | 898600 | National | 7,575,733 | Regional | 3,825,261 | National | Regional | 11,471,794 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 890100 | 877900 | National | 7,575,733 | Regional | 3,715,813 | National | Regional | 11,362,381 |
| 910800 | 857200 | European | 7,837,650 | International | 3,625,960 | European | European | 11,428,226 |
| 931500 | 836500 | European | 8,008,409 | International | 3,536,860 | International | International | 11,508,179 |
| 952200 | 815800 | International | 8,217,948 | International | 3,447,695 | International | International | 11,686,688 |
| 972900 | 795100 | International | 8,441,993 | International | 3,365,928 | International | International | 11,821,801 |
| 993600 | 774400 | International | 8,441,861 | International | 3,280,716 | International | International | 11,732,779 |
| 1014300 | 753700 | International | 8,441,835 | International | 3,191,689 | International | International | 11,643,747 |
| 1035000 | 733000 | International | 8,441,861 | International | 3,102,661 | International | International | 11,564,260 |
| … | … | … | … | … | … | … | … | … |
| 1304100 | 463900 | International | 8,442,075 | International | 1,952,245 | International | International | 10,419,224 |
| 1324800 | 443200 | International | 8,442,075 | International | 1,863,351 | International | International | 10,329,939 |

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