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Optimal Production Planning for the Virgin Olive Oil Elaboration Process ⋆

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Abstract: The quality and obtained quantity of Virgin Olive Oil is bounded by the characteristics of the olives to be processed, and further determined by the influence of the process variables during the actual elaboration. Since the quality of the olives evolves during the harvesting season, it is relevant to consider when to harvest the olives in order to maximize the profit over the whole season. This work proposes a method to determine an optimal production plan for the whole harvesting season and presents the results obtained in its application to four different scenarios.

Keywords: Production planning and control; Intelligent decision support systems in manufacturing.

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1. INTRODUCTION

The production of virgin olive oil (VOO) is an important economic activity carried out in more than 30 countries. The world average VOO production in the period 2006–2012 was 2,934,000 t, which supposes a 5% increase over the average of the 2000–2006 period (International Olive Council, 2013). This tendency is likely to continue in the near future, as olive trees planted during the last years are starting to increase their production.

The quality of the VOO is bounded by the quality of the olives to be processed, and further determined by the influence of the process variables during the actual elaboration. Obviously, the amount of VOO produced also depends critically on the characteristics of the incoming olives and the values of the process variables. Quality and quantity represent a trade-off, since the values of the process variables that preserve the quality tend to lessen the amount of VOO produced, and vice versa (Di Giovacchino et al., 2002b; Cano Marchal et al., 2011).

Hence, in order to produce VOO from a batch of olives, a decision must be made about whether the aim is to maximize the quality or the stress is in obtaining the maximum possible amount of VOO. This decision, thus, establishes a production objective which requires a consequent selection of the values of the process variables to fulfill this pursued objective.

Background Plenty of research efforts have been devoted to determine the influence of the process variables in the quality and quantity of the VOO produced, see, for instance (Clodoveo, 2012; Di Giovacchino et al., 2002a; Inarejos-García et al., 2009). This research is of great importance, since it is the interplay of the process variables that will finally determine the output of the process, i.e. the actual quality and quantity of VOO obtained. Nevertheless, it is also relevant to determine what would be the *best* production objective for a given batch of olives, assuming that we intend to maximize the economic profit of the activity. In Cano Marchal et al. (2013), this problem is considered in the context of a general system for defining and updating suitable set points for the VOO elaboration process, and some considerations about how to approach it are hinted.

However, once a batch of olives has arrived to the factory, an upper bound on the quality has already been set by the decision of when those olives were harvested (Gutiérrez et al., 1999; Jiménez Herrera et al., 2012). Since the quality of the olives evolves during the harvesting season, a pertinent question would be to consider when to harvest the olives in order to maximize the profit over the whole season.

Problem Statement The objective of this work is to obtain a method capable of determining an optimal production plan for the whole harvesting season, i.e., define what amounts of VOO of which qualities maximize the profit of the company, given pertinent restrictions.

More formally, the objective is obtaining a production plan P defined as a temporal sequence of vectors p_i:

$$P = [p_1 \, p_2 \, \cdots \, p_i]$$

where $p_i = [n_i \, q_i]^T$ and

- n_i represents the amount of oil to be produced , and
- q_i the quality objective;

as a solution of an optimization problem where the objective is maximizing the economic revenue of the company. Throughout the paper the subindex i indicates the considered time period.

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Table 1. Definition of variables involved in the optimization problem

SYMBOL	VARIABLE
P	Production plan
p	Production objective for a time period
n	Quantity of oil produced
a	Quantity of olives processed
q	Quality of oil to be produced
F^W	Fat content of the olives in wet base
F^D	Fat content of the olives in dry base
H	Water content of the olives
E	Extractability of the olives, defined as percentual content of oil in the pomace, expressed in dry base
R	Ripeness index
c^p	Elaboration cost (Euro/kg olive processed)
s	Sale price of the oil
m	Commercialization method
c^d	Commercialization cost
h	Harvesting method
c^h	Harvesting cost

The rest of the paper is organized as follows: Sec. 2 covers the theoretical part of the work, presenting the objective function and the restrictions and models considered. Section 3 shows some results obtained using the proposed method for different scenarios and Sec. 4 presents the conclusions of the work and the future research lines.

2. METHOD

The method developed employs the definition of an optimization problem which includes the relations of the different variables involved in the VOO elaboration and marketing as constraints to the problem of maximizing the profit.

Table 1 includes the definition of the considered variables and Fig. 1 depicts a conceptual map of their relations. The orange blocks constitute the models providing the characteristics of the incoming olives independent of the actual VOO elaboration process, i.e., the characteristics of the olives just before being harvested. Yellow blocks include the influence of the harvesting and the VOO elaboration process; with beige blocks covering the business related aspects. In turn, the blue ellipsoidal blocks represent the costs and prices involved in the model; green blocks are intermediate variables of the model and the red ones represent the decision variables. The following subsections detail each of these components.

2.1 Olive Properties Models

The most evident restrictions to be considered in the system are those imposed by the olives. Since the characteristics of the olives evolve in time, a model of this evolution is required to provide the value of the variable exclusively as a function of the time period considered, i.e.: $x_i = f(i)$. Here, x_i denotes a generic variable and i represents the time period considered.

Ripeness, Fat Content and Humidity Evolution The characteristics of the olives relevant to the problem are the ripeness (R_i), the fat content (F_i^D) and the humidity (H_i). The ripeness of the olives (R_i) is related with the maximum VOO quality attainable and the extractability (E_i) (García et al., 1996). In this paper, the data provided in Jiménez Herrera et al. (2012) are used for this model and implemented as a look-up table.

The fat content (F_i^D) obviously determines the total amount of oil produced, while the humidity of the olives (H_i) affects also the extractability (Cert et al., 1996). Here, the data used is extracted from (Gutiérrez et al., 1999) for F_i^D. Surprisingly, data of the evolution of H_i was not included in the consulted works, so typical evolution data was provided by experts in VOO elaboration.

Olive Composition Formula The relation between the amount of olives processed and the oil obtained depends on the composition of the olives and the amount of oil that the process is capable of extracting. Performing a mass balance on the inputs and outputs of the process, the following relation can be derived:

$$n_i = a_i(1 - \frac{H_i}{100})(\frac{F_i^D - E_i}{100})(1 - \frac{E_i}{100})^{-1}, \qquad (1)$$

where F_i^D and H_i account for the composition of the olives, and E_i gathers the influence of the process in the total oil recovery.

Maximum attainable quality model The modeling of q_i^{max} as a function of R_i is an interesting problem and there are several works regarding this relation, see, for instance (Gutiérrez et al., 1999; Salvador et al., 2001). In this paper, the data provided by Jiménez Herrera et al. (2012) is used and implemented as a look-up table. These data refer to olives that are on the tree.

2.2 Definition of Products

In order to tackle the definition of the optimization problem, it is cast as a product selection problem. Each considered product has the following distinct attributes:

- Required quality (q_k^{min})
- Commercialization method (m_k)

i.e., a product is characterized by its quality and the way it is commercialized. Note that there may be two products with the same required quality and different marketing methods, which allows to model the possible different costs and incomes due to different commercialization strategies for a single VOO quality. Throughout the paper, the index k references the different products considered.

Required quality implications The definition of the required quality for the product (q_k^{min}) implies restrictions on the following variables:

- Quantity of oil produced at a given time period $n_{i,k}$: if the maximum attainable quality, as bounded by the characteristics of the incoming olives, is below the required quality, then this product cannot be produced. This requirement renders the constraint:

$$n_{i,k} \leq \begin{cases} 0 & \text{if } q_{i,k} \leq q_k^{min} \\ \overline{n}_{i,k} & \text{otherwise}, \end{cases} \qquad (2)$$

with $\overline{n}_{i,k}$ defining a bound based on the maximum processing capacity for the considered time period.

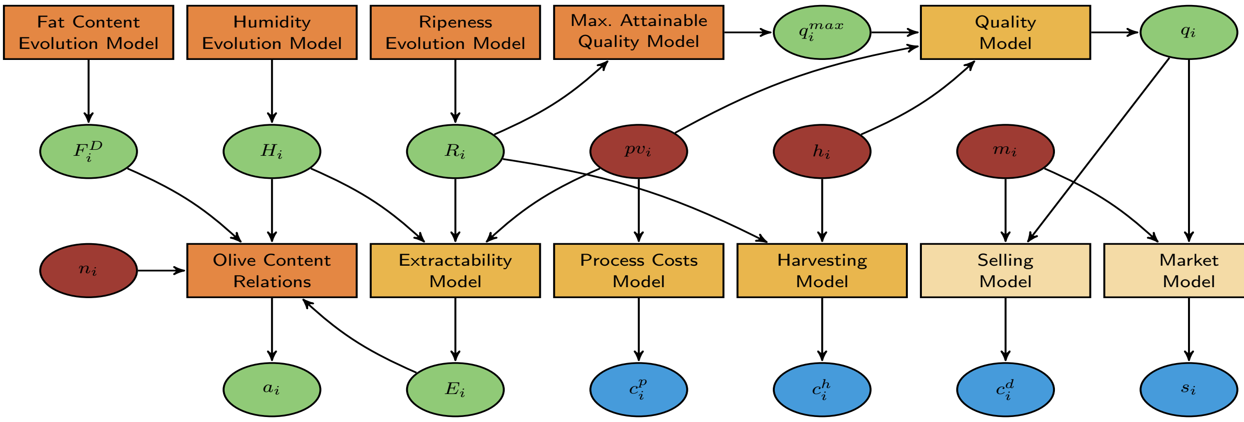

Fig. 1. Conceptual map of the involved variables and models in the optimal production planning for VOO elaboration. The orange blocks constitute the models providing the characteristics of the incoming olives independent of the actual VOO elaboration process. Yellow blocks include the influence of the harvesting and the VOO elaboration process and beige blocks model the business related aspects. Blue ellipsoidal blocks represent the costs and prices involved in the model; green blocks are intermediate variables and the red blocks are the decision variables.

- Process variables: the objective of obtaining a certain quality (q_k^{min}) imposes a restriction on the possible values of the process variables:
$$pv_{k,i} \in \{pv \mid q(pv, q_i^{max}) \geq q_{i,k}^{min}\}. \tag{3}$$
Here, $q(\cdot)$ stands for the model relating q_i, q_i^{max} and pv_i – this model is further treated on Sec. 2.3. Note that this selection of process variables affects also the extractability $E_{i,k}$ through the extractability model, as well as the process costs.
- Harvest method: analogously to the case of pv_i, a restriction is also imposed on the harvest method to be used, which, in turn, affects the harvest cost:
$$h_{k,i} \in \{h \mid q_h(h, q_i^{max}) \geq q_{i,k}^{min}\}. \tag{4}$$
Again, $q_h(\cdot)$ stands for the model relating q_i, q_i^{max} and h which will be expanded in Sec. 2.3.

Commercialization method implications In turn, the relations of the assigned commercialization method (m_k) comprise:

- Total quantity of product to be sold for the whole season: this quantity is bounded by the share of market of the company, thus the following constraint applies:
$$\sum_i^f n_{i,k} \leq \bar{n}_k. \tag{5}$$
- Commercialization cost: this cost includes the packaging, marketing and distribution costs. It will also be dependent on the company structure. This cost may depend on the total amount of product sold due to scale economies.
$$c_k^d = c^d(\bar{n}_k). \tag{6}$$
Note that there is no i index in the equations, since the cost is considered to be constant for the whole season.
- Sale price: obviously, a sale price must be defined for each product. The selection of the optimum sale price and its implications on the total quantity of product sold $\bar{n}_k$, and, trough this variable, in the commercialization cost c_k^d, represents an interesting optimization problem out of scope of this paper. Here, we suppose that the pricing policy of the company has already been decided.

2.3 Process Relations Models

The relations between quality (q), amount of oil recovered (n) and costs with the different variables and alternatives throughout the VOO elaboration process are addressed in the following subsections.

Harvesting model The harvesting methods can be classified in two major groups:

- Methods that separate olives coming from the tree from olives already in the ground, and
- Methods that mix olives coming from the tree and the ground.

Olives that have fallen to the ground present poor quality characteristics, due to the chemical reactions that begin to take place (García and Yousfi, 2007). Therefore, methods that mix olives cause a decrease of the potential quality that could be obtained if only olives coming from the tree were to be harvested. However, these methods tend to offer lower costs, since they require lower manual labor (Vilar Hernandez et al., 2010).

Although different non-mixing harvesting methods have been reported to show different effects on the quality of the obtained VOO (Yousfi et al., 2012), for this paper we focus on the difference between the two major groups. The ratio of fallen/tree olives is a parameter of importance, as determines the decrease of quality due to the mixture of qualities. The amount of fallen drupes increases as the harvesting season advances, due to the reduction of the retention force of the olives as they ripen. Meteorological phenomena, such as high intensity wind, may increment the amount of fallen olives in stages where they would normally still be on the tree. Despite the bibliographic research carried out, no published data of the typical evolution of this parameter was obtained. So, the resulting preliminary model used for the paper employed a linear model for the amount of fallen olives based on estimative data provided by VOO elaboration experts. However, there is published data regarding the quality evolution of harvested (or fallen) olives in García et al. (1996), which was included in the model. This data, together with the data available in Jiménez Herrera et al. (2012) allows to estimate the quality of the harvested olives. Thus, the model can be expressed as:

$$r_{c,i} = f(i) \tag{7}$$

$$q_{c,i} = f(i, r_{c,i}, i_c) \tag{8}$$

$$q_{h,i} = f(r_{c,i}, q_{c,i}, q_i^{max}, h) \tag{9}$$

with

- $r_{c,i}$: percentage of fallen olives at time i,
- $q_{c,i}$: quality of the fallen olives at time i,
- $q_{h,i}$: quality of the harvested olives.

Another effect worth considering is the different harvest cost due to the different facility to separate the olives from the tree (Ferguson, 2006), thus influencing the productivity and, consequently, the harvesting cost. Again, the estimation of the overcost due to this effect was provided by experts. This effect may be formalized as:

$$c^h = c^h(R). \tag{10}$$

Process quality and extractability models The influence of the different process variables on the VOO quality (q) and the extractability (E) are included in these models. As commented previously, plenty of research effort has been devoted to identify and describe these relations.

The model of the influence of the process variables on the quality and the extractability is taken from the subsystems A and B of the system proposed in Cano Marchal et al. (2013). In this paper, the relation between quality objective and expected extractability was established via a first subsystem (A). Then, a second subsystem (B) provided initial set points for the process variables as a function of the quality objective. The process variables considered were:

- t_s: the time that the olives are stored previous to their being processed (hours),
- C: the size of the sieve of the crushing mill (mm),
- A_t: the addition of microtalc (kg. talc / kg. paste),
- t_b: the kneading time inside the thermomixer (minutes),
- T_b: the kneading temperature in the thermomixer (°C).

Given the quality requirement fixed in the product definition, these models provide the values of extractability and process variables for each product. Note that, within this scheme, the predicted properties of the olives are not used to modify the values of these variables. The most important effect to model is the imposibility of obtaining a product if the quality of the olives is not adequate, and this is already modeled in Eq. 2. Some minor adjustments of the process variables might be plausible given the characteristics of the olives, but their influence in the system would be exclusively through the process costs and not too relevant, so, in order to simplify the problem, the value of the process variables is supposed independent of the characteristics of the olives.

2.4 Process Costs Models

Once the values of the process variables are defined, the computation of approximate process costs can be performed via simple relations. The values of t_s and C do not have much influence in the process costs, and can be omitted. The cost associated with the use of microtalc can simply be modeled by:

$$c_{A_t} = A_t \cdot p_{talc}, \tag{11}$$

where p_{talc} is the price per kg. of the microtalc employed. The cost of heating the olive paste can be estimated as:

$$c_{T_b} = (T_b - T_{amb}) \cdot c_{paste} \cdot \frac{p_{fuel}}{pci_{fuel}}, \tag{12}$$

with c_{paste} being the heat capacity of the olive paste, pci_{fuel} and p_{fuel} the lower heating value and price of the fuel respectively.

The value of t_b does not significantly influence the total processing cost, since it is the rate of flow of paste into the decanter that determines the production rate and, consequently, the amount of time that the factory must be operating in order to process the olives. In Cano Marchal et al. (2013), the influence of this variable was not considered, so its effect is also neglected here. Note that different t_b are achieved by simply varying the total volume of olive paste contained in the thermomixer for a given flow rate.

Lastly, the man labor cost in the factory is basically independent of the quality that is being produced, and can also be disregarded in this initial overview.

The analysis above finally renders the simple process cost estimation equation:

$$c^p = c_{A_t} + c_{T_b} \tag{13}$$

2.5 Optimization Problem Definition

In the previous subsections the different relations and constraints affecting the system have been established. In this subsection the optimization problem is formalized.

First, some additional constraints that apply to the problem must be considered:

- Bound on the total amount of olives to be harvested on the whole season, since there is an obvious natural limit on the disponibility of olives for each company:

$$\sum_{i=1}^{f} \sum_{k=1}^{k_f} a_{i,k} \leq \bar{a}. \tag{14}$$

- Bound on the total amount of olives to be processed per time period: this bound may be imposed by either the installed processing capacity of the factory or by the harvesting capacity:

$$\sum_{k=1}^{k_f} a_{i,k} \leq \bar{a}_i. \tag{15}$$

- Finally, the olives processed must be either positive or zero:

$$a_{i,k} \geq 0. \tag{16}$$

In Fig. 1, the variables $[n_i, pv_i, h_i, m_i]$ are marked as decision variables, i.e., variables whose values must be

Table 2. Sale prices in each scenario (Euros/kg)

PRODUCT	Extra Sup.	Extra	Virgin	Lampante
SCENARIOS IA-IB	4	2.71	2.51	2.36
SCENARIOS IIA-IIB	3.5	1.75	1.65	1.59

determined by the solution of the optimization problem for each time period considered. However, the introduction of the concept of product allows to change the decision variables to $n_{k,i}$, since, as commented above, the definition of (q_k^{min}) for each product fixes the values of pv_i and h_i, while the selection of m_k obviously fixes m_i. The problem, thus, is reduced to chosing the quantity of each product to be produced for each time period considered.

Since the production costs are naturally modeled as proportional to the amount of olives processed, and the commercialization costs proportional to the quantity of VOO sold, the objective function can be defined as:

$$J = \sum_{i=1}^{f} \sum_{k=1}^{k_f} n_{i,k}\,(s_k - c_k^d) - a_{i,k}\,(c_k^p + c_k^h) \qquad (17)$$

with $i \in [1, f]$ being the index considering the different time periods and $k \in [1, k_f]$ regarding the different defined products.

Gathering the objective function with the constraints presented in the previous subsections, the optimization problem is defined as:

$$\begin{array}{ll} \textbf{max} & J \\ \textbf{subject to:} & \text{Eqs. } (1) - (16). \end{array}$$

3. RESULTS

In order to illustrate the proposed method, a set of four products was defined based on the usual quality clasification of VOOs. The Extra Superior product is supposed to be sold bottled, while the rest of products are supposed to be sold in the bulk market. Consequently, a sell limit is considered for the Extra Superior, while no bound is set for the other products. The required quality for each product is plotted in Fig. 2 using dashed lines.

Four scenarios have been considered based on two different values for two parameters. First, two different sets of sale prices have been taken from the average bulk sale prices for the Extra, Virgin and Lampante qualities from the Poolred system (Poolred, 2013). Data for Scenarios I are taken from the June-July period of 2013, while Scenarios II considers the same period of 2012. For the Extra Superior product, since there are no published data, the sale price has been fixed as a typical sale price for that product. The different prices are gathered in Table 2.

The second parameter considered is the quality evolution of the olives in the orchards. Scenarios A consider a regular evolution of the quality, while scenarios B consider the situation when some factor, such as a plague or hail, supposed to occur on the first week of november, provokes a substantial decrease of the quality. Figure 2 depicts the evolution of the quality for the considered scenarios.

The time unit used is weeks, and 20 time instants are considered. The problem defined for each scenario was

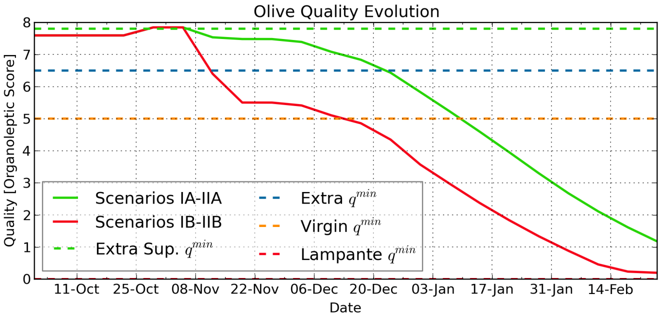

Fig. 2. Quality evolution of the olives for the different scenarios considered.

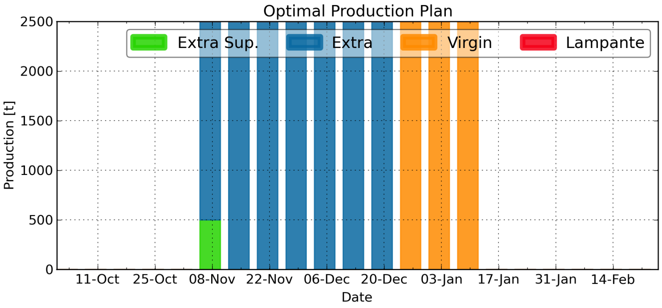

Fig. 3. Optimal production plan for scenario IA.

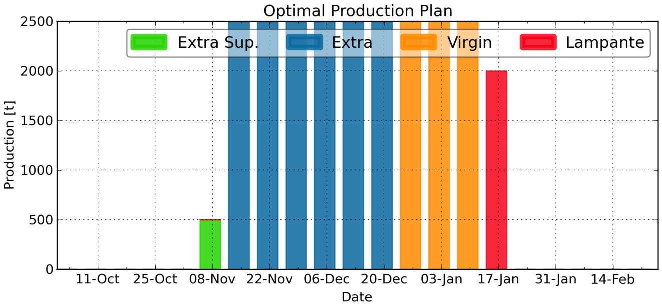

Fig. 4. Optimal production plan for scenario IIA.

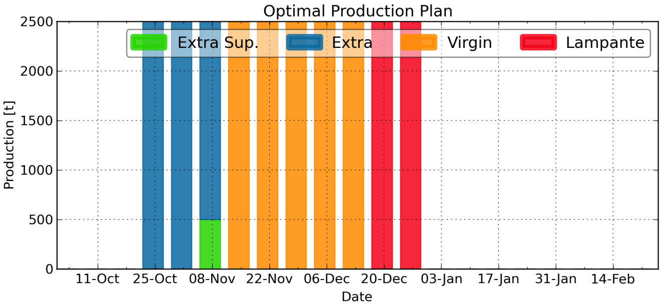

Fig. 5. Optimal production plan for scenario IB.

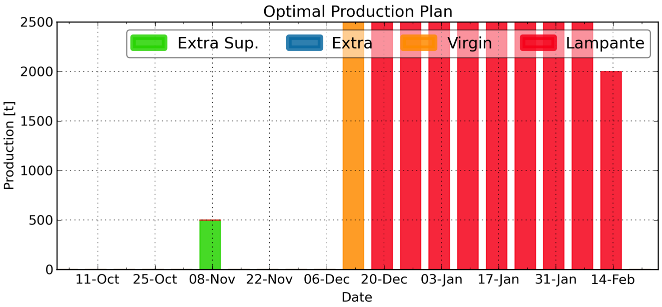

Fig. 6. Optimal production plan for scenario IIB.

solved using OpenOpt (Kroshko, 2007) with the *glpk* solver.

Figure 3 plots the optimal production plan (P), for scenario IA, while Fig. 4 depicts scenario IIA. As can be seen, both scenarios are quite similar, just implying a small shift in production towards the final part of the harvest season for IIA. The comparison between scenarios IA and IB (Fig. 5) shows the convenience of starting to harvest earlier when the quality drops sharply and the spread between prices for the products is high.

The remarkably different plans provided for scenarios IB and IIB (Fig. 6) highlight the fact that if the spread of prices is not high enough, and the base quality is low, it is better to plan the production just aiming to maximize the amount of obtained oil. Finally, it is worth noting that the production of Extra Superior remains constant between scenarios, and limited by the selling capacity considered. The fact that it is produced as late as possible is justified by the increasing fat content and extractability due to the evolution of the ripeness of the olives.

4. CONCLUSION

In this paper the problem of obtaining an optimal production plan for the VOO elaboration has been regarded. The different factors that must be considered and the relations between variables have been pointed out. Then, based on data provided by bibliography and experts, some results have been presented for four different scenarios.

Further work in obtaining better data for the different models is desiderable. In particular, the selling and market related and harvesting models may be refined. Furthermore, the obtention of different models for different olive cultivar varieties might be of interest.

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