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A bi-objective optimization model for tactical planning in the pome fruit industry supply chain

Luis P. Catalá, M. Susana Moreno *, Aníbal M. Blanco, J. Alberto Bandoni

PLAPIQUI – Planta Piloto de Ingeniería Química (CONICET-UNS), Camino La Carrindanga km 7, Bahía Blanca 8000, Argentina

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ABSTRACT

In this work, a multi-period mixed integer linear programming formulation for the medium-term planning of the apples and pears supply chain is presented. Given the supply chain structure, demand data, and harvesting dates, the proposed approach integrates production, processing, distribution, and inventory decisions considering two conflicting objectives: profit and product supply shortage. The mathematical model is solved by using the lexicographic method to deal with the multi-objective optimization. The system is analyzed in the face of changes in storage, processing and transportation capacities. Major results indicate that in order to minimize supply shortage (leading objective) in the second part of the season, beneficial trade opportunities have to be missed along the year with the consequent reduction in the total profit (subordinated objective). To illustrate the approach, a pome fruit industry located in the "Alto Valle de Río Negro y Neuquén" Argentine region is considered as a case study.

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1. Introduction

The significant uncertainty and increasing pressures of the global marketplace have compelled companies to coordinate and integrate their business nodes (suppliers, industrial facilities, distributors, and clients) as supply chains in order to improve management. A supply chain (SC) is an organizational scheme where network's actors coordinate activities ranging from acquisition of raw material to delivery of final products to clients in order to attain global objectives.

Despite supply chain management is a mature field, to the best of our knowledge, fresh food SC and, particularly, the fresh fruit SC, have not been systematically addressed in the open literature.

The particular case of the pome fruit industry (pears and apples) SC problem pose several challenges due to specific distinctive characteristics.

On the one hand, apples and pears are perishable goods so they lose quality with time. Under normal conditions, these fruits have a limited lifetime which is inferior to the business cycle (one year). Beyond this period, they cannot be commercialized as fresh fruit because they do not meet market standards (Shah et al., 2005; Pahl and Voβ, 2014). Therefore, the inherent perishability of the fruit confines the possibilities of processing and commercialization to a reduced portion of the time horizon. In order to extend the marketable periods, cooling technologies have been implemented along the entire SC (Verdouw et al., 2010). In this regard, controlled atmosphere storage is probably the most revolutionary technology since the fruit can be safely stored up to 12 months (Studman, 2001).

On the other hand, the fresh fruit business is a seasonal activity since the raw material for producing each product is available during a relatively short harvesting period for each variety (Verdouw et al., 2010). Additionally, the availability of fruit depends significantly on nature, since, climatic conditions and pests make fruit production uncertain.

Another special feature of this activity is that unlike classical order- or demand-driven SCs (Perea-López et al., 2003), pome fruit SCs are production-driven systems since they are pushed by the fresh fruit offer produced in farms, which determines the product availability for future commercialization (Masini et al., 2008). In the former, also known as pull systems, the flow of information goes from end customers to suppliers in opposite direction to the material flow (Beamon, 1998; Subramanian et al., 2013). In this case the objective is to meet demands in a timely and cost-effective manner (Cecere et al., 2004). In contrast, in the fruit business, the estimated production is in a large proportion pre-assigned to clients in negotiations carried out before the beginning of the season. Therefore, the produced material should be managed not only attempting to satisfy as close as possible the already established commitments but also to allocate a large amount of necessarily generated sub-products. As a result, the

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* Corresponding author.
E-mail address: smoreno@plapiqui.edu.ar (M.S. Moreno).

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information flows in both directions along the chain (Verdouw et al., 2010).

According to van Donk et al. (2007), abovementioned characteristics hamper the integration of the different nodes in the SC, especially among farmers, packaging plants and juice producers. For example, fruit producers generally pursue the goal of obtaining higher production volumes which can be achieved by leaving the fruit on the tree as long as possible. Nonetheless, the fruit not only grows but also continues to ripen, putting in risk its preserving capacity and, as a consequence, preventing its future access to fresh fruit markets due to quality losses. For this reason, decision makers prioritize the fruit condition over its gauge (size or weight). Planning the SC in a coordinated manner would facilitate addressing this type of tradeoffs.

As far as we know, however, only a few studies appearing in the literature deal with the fresh fruit SC problem optimization. Generally, such works focus on a single node of the network. Broekmeulen (1998) proposed a tactical decision model for the operations of distribution centers of perishables (vegetables and fruit). The model allows determining the optimal assignment of products to storage zones of the center in order to minimize loss of quality. Blanco et al. (2005) formulated a multiperiod linear programming (LP) model for the tactical planning of a packaging plant, which is the core facility of the pome fruit industry SC. Given maximum processing and storage capacities, the optimal flows of fruit and inventories within the facility were obtained over a time horizon of one year divided in one-day periods.

One of the earliest attempts for integrating different echelons in the pome fruit SC was reported by Masini et al. (2003). They developed a multiperiod Mixed Integer Linear Programming (MILP) model for the mid-term tactical planning problem. However, the scope of this work is limited because it considers a one-year time horizon divided in 12 monthly periods, which leaves short term scale details unattended. Ortmann (2005) described the SC for the exported fresh fruit in South Africa. He proposed LP formulations for optimizing the business by either minimizing the cost or maximizing the fruit flow through the network, with the purpose of finding bottlenecks in the infrastructure. Later, Masini et al. (2008) implemented a multiperiod LP model to be utilized as a decision making aid-tool in the negotiation instance of the business before the harvest season. The model calculates the daily production profile required to feasibly operate by maximizing the total net profit of the company. However, these proposals are also limited since, for example, do not considered the way ports and refrigerated storage operate.

In order to address the singular described features of the pome fruit industry, in this work a multi-objective optimization approach is proposed to tackle the SC problem. There exist several studies in the literature dealing with multi-objective optimization problems in SCs, which intend to model decision makers' preferences. From a mathematical perspective, most of them have resort to the ε-constraint method (Liu and Papageorgiou, 2013) which consist of transforming the multi-objective problem into a single-objective formulation where all, except one objective, are handled as constraints. Pareto-optimal solutions are then generated through proper selection of parameter ε. For example, Sabri and Beamon (2000) addressed a multi-objective model for integrating strategic and operational planning of a SC which considers cost, customer service level, and delivery flexibility as the ranking of objectives. Guillén et al. (2005) presented a multi-objective MILP model for the design problem of a SC taking into account the net present value, the demand satisfaction, and the financial risk as key goals. A two-stage stochastic programming strategy was adopted for handling demand uncertainty. More recently, Liu and Papageorgiou (2013) studied the production, distribution, and capacity planning of SCs using a multi-objective MILP formulation. For solving the problem, they first used the ε-constraint method with the total cost as the preferred objective, maintaining the total flow time and the customer service level as model constraints.

An alternative to the ε-constraint method is the lexicographic approach. In this approach the decision maker establishes a ranking of importance of the objective functions based in his/her preferences. A sequence of single objective optimization problems is therefore solved; each one with the solution of the previous problem as an additional constraint. This approach has been applied for example by Sawik (2007) for solving the multiperiod production scheduling problem. He presented a two-level decision problem where the top-level model maximizes the customer service level whereas the base-level model minimizes production fluctuations for reducing the unit production costs. Afterward, (2009) proposed a SC scheduling model using a three-level hierarchical lexicographic approach. First, the earliest release dates of customer orders are found by minimizing the inventory of parts and finished products. Second, the assembly schedule of the finished products and the assignment of customer orders to planning periods are determined and, finally, the manufacturing and supply of parts schedules are obtained. Several authors (Mavrotas, 2009; Pishvaee et al., 2012) have used this technique as a complement of the ε-constraint method for finding the extreme points of the Pareto frontier, while non-extreme points are calculated by changing the values of parameter ε.

Additional relevant work related to the multi-objective optimization of SCs is Mousavi et al. (2016, 2015a, 2015b).

The aim of this study is addressing the medium term planning in the multi-echelon pome fruit SC integrating, besides production nodes and industrial plants, the detailed operations of ports as well as both, conventional and controlled atmosphere cold storage facilities. The structure of the SC is fixed comprising different stages, namely production (own and third party farms), processing nodes (juice production and packaging plants), and distribution (local, regional, and overseas markets). A multi-objective MILP model is formulated considering the profit and the violation on demand as optimization criteria wherein the lexicographic method is adopted as solution method. The fundamental characteristic of this multiperiod MILP model is that it analyzes the SC as a whole for deciding from an economical point of view the best use of production, distribution, and storage resources in order to fulfill the established supply agreements. To illustrate the approach, typical SC of the pome fruit industry located in the "Alto Valle de Río Negro y Neuquén" Argentine region is considered.

2. Problem description

This approach poses a model for the tactical planning of a fruit industry SC involving apples and pears. Fig. 1 depicts the SC structure considered in this work which comprehends farms, packaging and processing plants, cold-storage facilities, transport options and various typical customers. Based on this representation the following problem is formally stated.

Two type of fruits (e = apple, pear) are available in the SC, each of them has V_e varieties v. A time horizon H of one year is discretized into time periods P, H_p. Each period has a specific length of several days $t \in DS_p$. The set HP_v only accounts for those time periods p where fruit variety v can be picked from the trees, which are determined according to initial and final harvesting dates for each fruit variety v, IEV_v and FEV_v.

In every period $p \in HP_v$, the amount of fresh fruit can come from own farms, PP_{vp}, and third-party fruit suppliers, $F3s_{vp}$. The production pattern of each fruit variety harvested each year in farms is described by average and standard deviation values ($\overline{PP_v}$ and σ_{PP_v}) based on historical data. It should be noticed that the whole

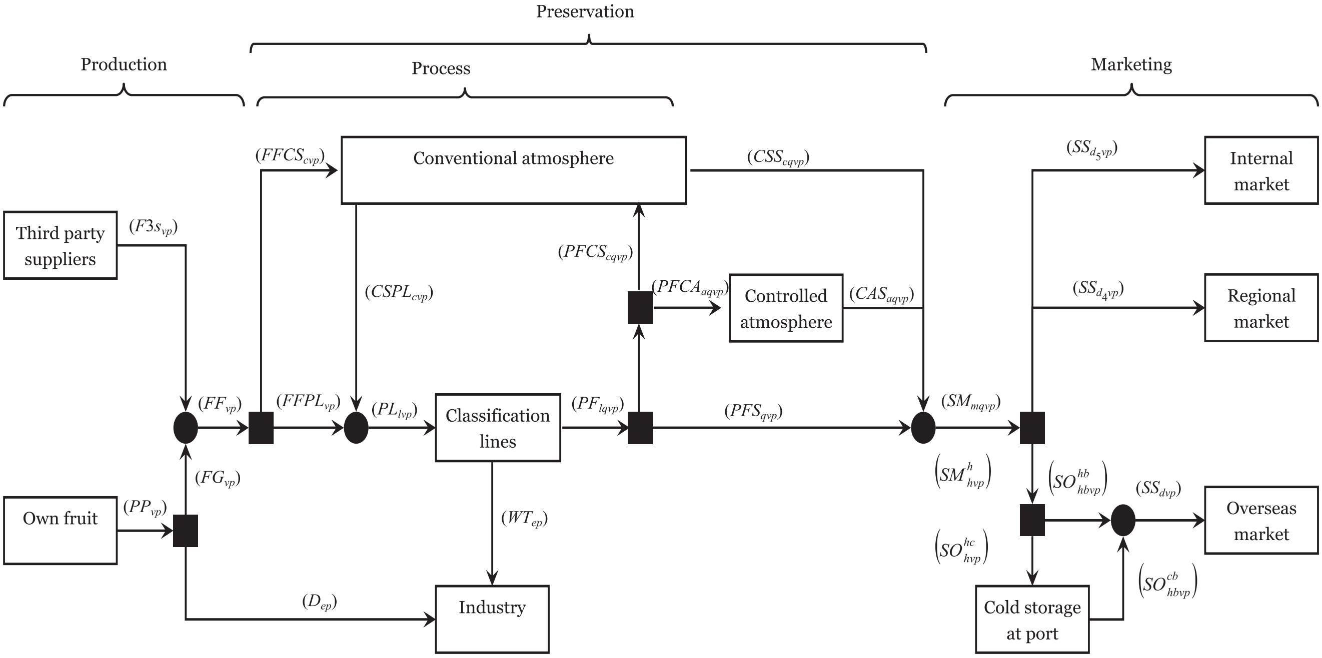


Fig. 1. SC structure for the pome fruit industry.

production of each variety is constrained to a rather narrow harvesting lapse along the year corresponding only to one or two periods within the planning horizon. A normal distribution is assumed in all cases. A fraction of fruit e, D_{ep}, coming from own farms cannot be sent to the packaging lines because it does not meet the attributes imposed by the marketplace. This amount, which corresponds to damaged or too imperfect fruit and therefore considered waste for packaging purposes, is dispatched directly to industrial facilities for concentrated juice production. It is worth highlighting that farms are active only during the harvesting periods ($p \in \cup HP_v$) which, in the southern hemisphere, comprise the first four months of the year.

The warm fresh fruit, FF_{vp}, is sent to the packaging plants which constitute the core of the pome fruit SC. At this node, a decision has to be made whether the fruit is temporarily cold-stored before being further processed or sent directly to the processing lines. Because of the high perishability of the fruit, packaging plants have different technologies for maintaining the fruit at an adequate temperature. In the studied region, two low-temperature storage technologies prevail, controlled atmosphere (CA) and conventional cooling (CS) chambers. Classified as well as not classified fruit may be stored in CS chambers, while only classified fruit should be kept into CA storage.

Typical activities in packaging plants include sorting, grading, washing, packing and cold storing and shipping of the fruits. Packaging plants have a number (PL) of classification or processing lines. Here, the incoming fruit is classified by the degree of imperfection and gauge (size or weight), resulting in a set Q of three different product qualities $q \in Q$ mainly differentiated by market preferences. As a result of this process, a second stream of fruit that does not meet commercial standards for fresh fruit, WT_{ep}, is separated as waste to be sent for juice production.

When the packing operation is completed at the end of the classification line, the fruit can be either cold-stored (i.e., $PFCS_{cqvp}$ and $PFCA_{aqvp}$) or immediately delivered to clients, PFS_{qvp}. Three typical different final markets m exist for a company of the region under study, namely local (domestic), regional, and overseas. The overseas market comprehends the following destinations: USA, Russia, and the European Union (EU), while Brazil constitutes the regional market. Set SD is therefore defined to cover all the considered destinations. For each type of fruit e, the demand profiles per destination $d \in SD$, S^T_{dep} are given.

Sales SS_{dvp} are made during the entire planning horizon for both domestic and regional markets, while for overseas clients they take place only during the first part of the year when there is no pome fresh fruit production in the northern hemisphere.

As previously mentioned, in this study, a bi-objective MILP model is proposed, whose objective functions are: (i) minimize the demand violation over the planning horizon and (ii) maximize of the economic benefit of the system. In the following subsections additional details of the system are provided.

2.1. Fresh fruit processing lines

Each line l works independently and has a minimum and maximum installed capacity which is related to the conveyor belt speed. Nevertheless, the processing capacity per day t is actually determined by the number of working shifts S ($s = 1,\ldots,S$) hired. Every change in fruit variety requires adjustments in the equipment items, causing idle times and consequent production losses. Since a several days period is adopted for the planning horizon, every line l is forced to process only one fruit variety v per day t. Regarding manpower, the plant can operate with up to three working shifts per day t (two eight-hour shifts and one seven-hour shift). In addition, labor regulations impose a minimum of 15 days hiring period for a new shift.

2.2. Conventional cold storage

Each conventional cold chamber c can accommodate either fresh or processed fruit (i.e., $FFCS_{cvp}$ or $PFCS_{cqvp}$). In order to avoid classified fruit being affected by the warmer temperature and sanitary conditions of not processed fruit, no mixing is allowed. Besides, only a certain type of fruit e can be stored at each chamber c, at a time.

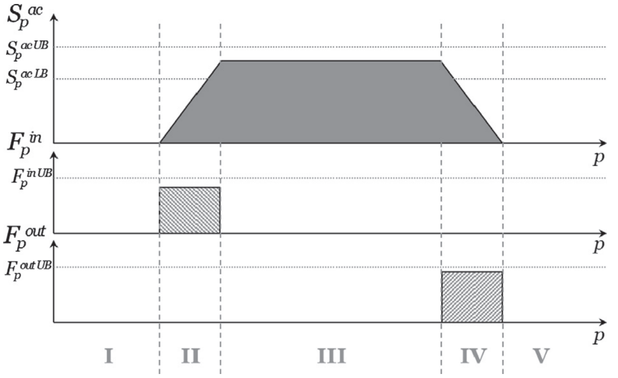
As pears and apples are climacteric fruits, they continue the ripening process inside the refrigerated chamber. Hence, the time that fruit can remain within the chamber is limited. In this work, the allowed maximum time in chamber *c* is calculated by adding a fixed time FCS_v to the final harvesting date for each variety *v*, FEV_v. Although this is an approximation, it represents qualitatively the chamber's operation. When the limiting time is reached, the remaining fruit kept in the chamber has to be traded.

2.3. Controlled atmosphere storage

The principle of CA storage is to maintain fruit in a relatively closed storage environment, with specific controlled concentrations of oxygen, nitrogen, carbon dioxide and others gases. Under these conditions the fruit can be stored for about 1 year without any appreciable loss of quality. The CA storage requires airtight refrigerated rooms that are sealed after fruits are stored inside (and must not be opened for at least 120 days after the seal is affixed).

Every CA chamber *a* is operated in a series of steps: (i) filling, (ii) airtight sealing, (iii) opening, and (iv) emptying, which establishes the five stages depicted in Fig. 2. During the first stage, the chamber is empty and available for being used (Stage I, Fig. 2). If the chamber is not used at all, Stage I lasts the entire time horizon. The second stage (Stage II, Fig. 2) corresponds to the filling step which comprehends the period when the storage starts to fill up till the moment that it is sealed. Here, a non-zero feed stream exists F_p^{in} with its value restricted by the maximum allowed flow rate, F_p^{inUB}. Also, the duration of this stage is upper bounded in order to avoid the effects of the ripening process that continues while the unit waits for being closed. The waiting stage (Stage III, Fig. 2) is the period in which the chamber stays closed and there are no material flows, hence, the stock of fruit S_p^{ac} is constant taking a value between the minimum and the maximum capacity levels, S_p^{acLB} and S_p^{acUB}. Moreover, the period length for this stage is limited by the minimum number of days that the fruit has to remain stored, OCA_v. The discharging stage (Stage IV, Fig. 2) is similar to the second one, but with a nonzero outflow of fruit F_p^{out}. Lastly, the duration of the final stage (Stage V, Fig. 2) has no limit and is determined from the period when the chamber is empty until the end of the planning horizon.

To sum up, the operation of each of CA storage follows the aforementioned sequence with the restriction that the mixing of fruit species is not allowed. It should be noted that, unlike conventional cooling units, each CA chamber is used only once during the whole time horizon.



Stage	Y	F_p^{in}	S_p^{ac}	F_p^{out}
I	$Y_{ap}^{w}=1$	$F_p^{in}=0$	$S_p^{ac}=0$	$F_p^{out}=0$
II	$Y_{ap}^{f}=1$	$F_p^{in}\le F_p^{in\,UB}$	$S_p^{ac}\le S_p^{acUB}$	$F_p^{out}=0$
III	$Y_{ap}^{c}=1$	$F_p^{in}=0$	$S_p^{ac\ LB}\le S_p^{ac}\le S_p^{ac\ UB}$	$F_p^{out}=0$
IV	$Y_{ap}^{p}=1$	$F_p^{in}=0$	$S_p^{ac}\le S_p^{ac\,UB}$	$F_p^{out}\le F_p^{out\,UB}$
V	$Y_{ap}^{e}=1$	$F_p^{in}=0$	$S_p^{ac}=0$	$F_p^{out}=0$

Fig. 2. Scheme of CA chamber operation.

2.4. Markets

Market requirements for fruit quality differ. Here, overseas markets only demands first-quality products ($q = 1$) while Brazil has been traditionally more flexible importing both first- and second-quality fruits ($q = 1, 2$). The domestic fruit market consumes all the three qualities. Besides, as every market *m* purchases different type of the fruit varieties *v*, a set AQ_m is defined that includes the varieties *v* that market *m* prefers. Shipment of packaged fruit is performed by refrigerated trucks to final clients in the regional and local markets and to ports for the overseas market. The capacity of the tracks, TC_m, and its number, NT_m, depends on the market involved.

It is worth highlighting that sales are assumed to be accomplished when final products leave the packing facility for both regional and domestic markets whilst for overseas clients the marketing is different. To clarify this point, Fig. 3 shows the flow of materials at the port and its operation. Each port *h* possesses refrigerated storage facilities, thus when the fruit comes from the packing plants it can be either kept cold stored until the arrival of the ship *b* or directly loaded on the marine vessel if it is already tied-up at berth. The gray dotted lines in Fig. 3 depict the operations performed once the ship is at the berth. Also, the estimated arrival ETA_{bh} and departure ETD_{bh} times for each vessel *b* at port *h* are assumed to be given. Under these conditions, the sales for the overseas clients are considered finished when the ship leaves the last Argentinean port.

2.5. Discretization of the planning horizon

As previously mentioned, a one-year planning horizon *H* was discretized in several time periods *p* that may have different length measured in days *t*, H_p. The division is performed according to particular milestones that occur during the season. Specifically, the selected milestones for dividing the time horizon are the initial and final harvesting date for each fruit variety *v*, IEV_v and FEV_v; the time limit for keeping fruit in CF storage FCS_v, the estimated time of departure for each vessel ETD_{bh}, and the shortest time that the fruit has to remain stored in CA chambers, OCA_v. For illustrative purposes, Fig. 4 shows the division of the time horizon for a hypothetical example where 2 fruit varieties, 2 vessels, and no CA chamber are considered.

3. Model formulation

The tactical planning model for the pome fruit SC mostly involves mass balances in each node of the system, together with capacity restrictions. In the following subsections, the detailed constraints are described. The involved objective functions are also presented.

3.1. Incoming fruit

The main input data to the tactical planning model is the amount of fruit per variety *v* produced in own farms in every time period *p*, PP_{vp}, together with the percentage of discarded fruit in the orchards, w_{vp}^{pp}. Average and standard deviations values for such parameters obtained from historical records are reported in Appendix A. Additionally, for each fruit variety *v*, the percentage of the total production picked in every harvesting period *p*, DC_{vp}, is provided.

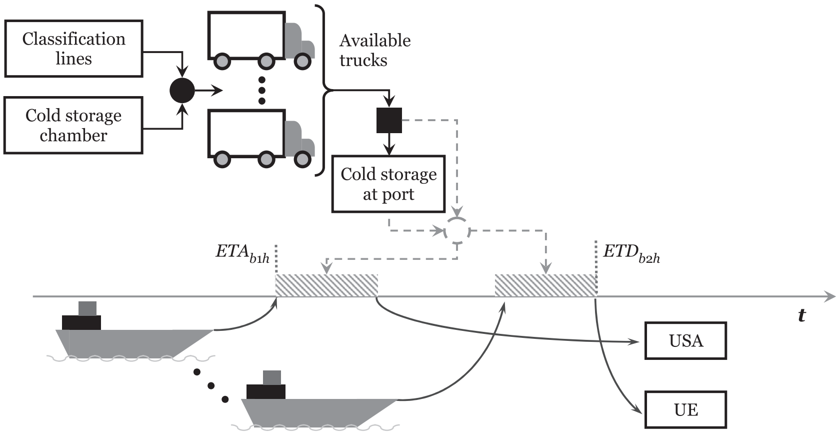


Fig. 3. Scheme of transportation and storage at port for overseas clients.

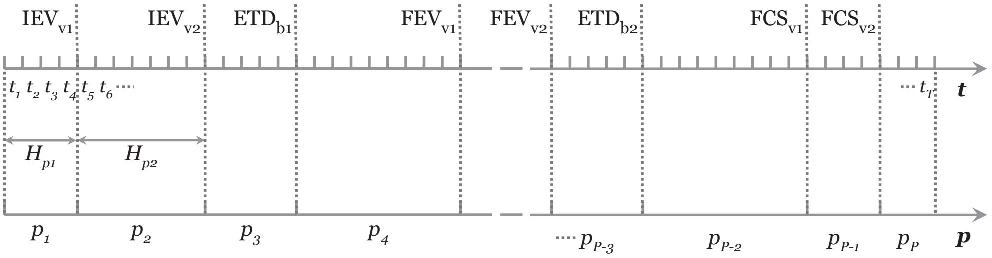


Fig. 4. Scheme of the time horizon.

$$PP_{vp} = DC_{vp}\ normal(\overline{PP_v}, \sigma_{PP_v}) \quad \forall v, p \in HP_v \tag{1}$$

$$w^{PP}_{vp} = normal(\overline{w^{PP}_v}, \sigma_{w^{PP}_v}) \quad \forall v, p \in HP_v \tag{2}$$

The amount of discarded fruit variety v in each harvesting period p, PI_{vp}, is therefore calculated as follows:

$$PI_{vp} = w^{PP}_{vp} PP_{vp} \quad \forall v, p \in HP_v \tag{3}$$

Thus, the remaining amount of variety v, PG_{vp}, available for processing in the packaging plant is given by Eq. (4).

$$PG_{vp} = PP_{vp} - PI_{vp} \quad \forall v, p \in HP_v \tag{4}$$

However, some amount of this fruit, FI_{vp}, can be also devoted for juice production if convenient.

$$PG_{vp} = FG_{vp} + FI_{vp} \quad \forall v, p \in HP_v \tag{5}$$

The total amount of variety v delivered to packaging lines in period p, FF_{vp}, is obtained by adding to the fruit from own farms, FG_{vp}, the fresh fruit purchased from third party farms, $F3s_{vp}$ (Eq. (6)).

The fruit used for juice production does not require a strict classification per variety and it is basically classified per type (pears and apples). Therefore, the amount of fruit from own farms directly sent to industry, D_{ep}, is determined in Eq. (7).

$$FF_{vp} = FG_{vp} + F3s_{vp} \quad \forall v, p \in HP_v \tag{6}$$

$$D_{ep} = \sum_{v \in EV_e} (PI_{vp} + FI_{vp}) \quad \forall e, p \in HP'_e \tag{7}$$

The amount of fruit purchased at third party suppliers cannot exceed certain limits (Eq. (8)). On the one hand, there is always a maximum amount of any variety available in the third party market, $F3s^{UB}_{vp}$; on the other, there is often a minimum purchasable amount due to suppliers' requirements, $F3s^{LB}_{vp}$.

$$F3s^{LB}_{vp} \leqslant F3s_{vp} \leqslant F3s^{UB}_{vp} \quad \forall v, p \in HP_v \tag{8}$$

3.2. Packaging plant

As mentioned before, part of fresh fruit v entering packaging plants in period p, FF_{vp}, is directly processed (classified), $FFPL_{vp}$, according to the number and capacity of the available classification lines, and the rest, $FFCS_{cvp}$, is derived to conventional cold chamber c. Only one packaging plant with several classification lines is considered in this formulation, which is the typical infrastructure for a large fresh fruit company in the region.

$$FF_{vp} = FFPL_{vp} + \sum_c FFCS_{cvp} \quad \forall v, p \in HP_v \tag{9}$$

Furthermore, the total quantity of fruit sent to the plant during period p, cannot exceed the maximum processing capacity per day, FF^{UB}_p:

$$\sum_v FF_{vp} \leqslant FF^{UB}_p H_p \quad \forall p \in HP_v \tag{10}$$

The amount of variety v processed in period p, expressed as the summation of quantities in each line l, PL_{lvp}, can be determined by Eq. (11) adding the fresh fruit entering the system, $FFPL_{vp}$, plus the non-processed fruit variety v cold-stored in chamber c, $CSPL_{cvp}$. Note that a new set HCS_v is considered for variety v, which includes those periods after the harvesting period in which the variety is allowed to remain cold stored in conventional chambers.

$$\sum_l PL_{lvp} = FFPL_{vp'} + \sum_c CSPL_{cvp} \quad \forall v, p' \in HP_v, p \in HCS_v \tag{11}$$

As already mentioned, each processing line l can handle only one fruit variety v per day t. To rigorously tackle this situation and recalling that period length H_p is composed by several days t, a binary variable X_{lvp} is introduced whose value is one if variety v is processed in line l in time period p, and zero otherwise. Thus, Eq. (12) implies that the varieties processed in line l in period p are limited by the period length H_p.

$$\sum_v X_{lvp} \leqslant H_p \quad \forall l, p \in \cup_v HCS_v \tag{12}$$

Constraints (13) and (14) are concerned with the capacity of each processing line at every period. The upper limit condition in Eq. (13) is expressed using a Big-M representation where the parameter BM is a sufficiently large number. The value of BM is the upper bound PL^{UB}.

$$PL_{lvp} \leqslant X_{lvp} BM \quad \forall l, v, p \in HCS_v \tag{13}$$

If fruit v is processed in line l in period p, PL_{lvp} has to be greater than the minimum capacity per shift, PL^{LB}, (Eq. (14)). Clearly, driven by Eqs. (13) and (14), this variable takes a null value if $X_{lvp} = 0$.

$$PL_{lvp} \geqslant PL^{LB} X_{lvp} \quad \forall l, v, p \in HCS_v \tag{14}$$

Eqs. (15) and (16) represent the processing capacity of line l that is determined by the number of shifts s hired in period p (i.e., $\sum_s Z_{sp}$) and the maximum and minimum installed capacity, respectively.

$$\sum_v PL_{lvp} \leqslant \sum_s Z_{sp} PL^{UB} \quad \forall l, p \in \cup_v HCS_v \tag{15}$$

$$\sum_v PL_{lvp} \geqslant \sum_s Z_{sp} PL^{LB} \quad \forall l, p \in \cup_v HCS_v \tag{16}$$

When a shift s is hired in time period p, i.e. $Z_{sp} = 1$, at least a number $|J|$ of working periods must be assured because of labor regulations. Because of this restriction, the following logical implication must be true:

$$(\neg Z_{s,p-1} \wedge Z_{sp}) \Rightarrow \left(Z_{s,p+1} \wedge Z_{s,p+2} \wedge \ldots \wedge Z_{s,p+|J|-1}\right) \tag{17}$$

The above proposition is guaranteed by the following constraints:

$$Z_{s,p-1} - Z_{sp} + Z_{s,p+j-1} \geqslant 0 \quad \forall s, j \in J, \ 1 < p \leqslant P - |J| + 1 \tag{18}$$

In packaging factories, a classification of each fruit variety according to its quality is performed. Thus, each line l separates an amount of fruit variety v with quality q in every time period p, PF_{lqvp}, together with an out of specification amount devoted to juice production, WPL_{lvp}. These quantities are calculated by Eqs. (20) and (21) where parameter g_{qvp} accounts for quality distribution of each variety and fw_{vp} is the fraction of waste generated at the packaging plant.

$$PL_{lvp} = \sum_q PF_{lqvp} + WPL_{lvp} \quad \forall l, v, p \in HCS_v \tag{19}$$

$$PF_{lqvp} = (1 - fw_{vp}) g_{qvp} PL_{lvp} \quad \forall l, q, v, p \in HCS_v \tag{20}$$

$$WPL_{lvp} = fw_{vp} PL_{lvp} \quad \forall l, v, p \in HCS_v \tag{21}$$

Then, the total amount of waste generated during the classification process WT_{ep} that is transported to industry for juice production is given by the following relation:

$$WT_{ep} = \sum_{v \in EV_e} \sum_l WPL_{lvp} \quad \forall e, p \in \cup_v HCS_v \tag{22}$$

Finally, classified fruit v in period p with quality q leaving the packaging plant encompasses the amount delivered to clients, PFS_{qvp}, and that allocated in cold storage, either conventional, $PFCS_{cqvp}$, or of the controlled atmosphere type, $PFCA_{aqvp}$.

$$\sum_l PF_{lqvp} = PFS_{qvp} + \sum_c PFCS_{cqvp} + \sum_a PFCA_{aqvp'} \quad \forall q, v, p \in HCS_v, p' \in ICA_v \tag{23}$$

3.3. Storage

3.3.1. Conventional low temperature storage

As it was mentioned, both processed and non-processed fruit can be stored in traditional cold storage chambers. The stock of cold non-processed fruit v in cold chamber c at the end of period p, S^{fnp}_{cvp}, is equal to the amount in storage at the end of the previous one, $S^{fnp}_{cv,p-1}$, plus the incoming fruit variety v from own farms, $FFCS_{cvp}$, less the cold-stored amount processed during period p, $CSPL_{cvp}$.

$$S^{fnp}_{cvp} = S^{fnp}_{cv,p-1} + FFCS_{cvp'} - CSPL_{cvp} \quad \forall c, v, p > IEV_v, p \in HCS_v, p' \in HP_v \tag{24}$$

Analogously, the stock of cold processed fruit v with quality q in chamber c at the end of period p, S^{fp}_{cvp} is given by:

$$S^{fp}_{cqvp} = S^{fp}_{cqv,p-1} + PFCS_{cqvp} - CSS_{cqvp} \quad \forall c, q, v, p > IEV_v, p \in HCS_v \tag{25}$$

Eqs. (26) and (27) enforce upper and lower bounds, respectively, for the total fruit stock kept in chamber c. Here, a new binary variable V_{cp} is used which is equal to 1 if chamber c is being used during period p; and zero otherwise. It must be noticed that the maximum inventory capacity for chamber c, S^{cUB}_{ce}, depends on the stored fruit e since apples and pears have different densities.

$$\sum_v \left(S^{fnp}_{cvp} + \sum_q S^{fp}_{cqvp}\right) \leqslant \max_e \{S^{cUB}_{ce}\} V_{cp} \quad \forall c, p \in \cup_v HCS_v \tag{26}$$

$$\sum_v \left(S^{fnp}_{cvp} + \sum_q S^{fp}_{cqvp}\right) \geqslant S^{cLB}_c V_{cp} \quad \forall c, p \in \cup_v HCS_v \tag{27}$$

According to Eqs. (28) and (29) the amount of fruit variety v either non-processed or processed entering in chamber c during harvesting periods has to leave it in some subsequent period over the tactical planning horizon.

$$\sum_{p \in HP_v} FFCS_{cvp} = \sum_{p \in HSC_v} CSPL_{cvp} \quad \forall c, v \tag{28}$$

$$\sum_{p \in HP_v} PFCS_{cqvp} = \sum_{p \in HSC_v} CSS_{cqvt} \quad \forall c, q, v \tag{29}$$

3.3.2. Controlled atmosphere storage

To represent the five stages involved in the CA storage operations (see Fig. 3): filling, airtight sealing, opening, and emptying steps, binary variables W^f_{ap}, W^c_{ap}, W^o_{ap}, W^e_{ap} are defined. In case of CA chamber a begins to fill up in period p ($W^f_{ap} = \text{True}$), it must be closed before reaching the filling time limit, Δp^f. This relationship can be expressed by the following logic proposition:

$$W^f_{ap} \Rightarrow \left(W^c_{ap} \vee W^c_{a,p+1} \vee \ldots \vee W^c_{a,p+\Delta p^f}\right) \tag{30.a}$$

These logic relations can be further transformed into inequalities as follows.

$$W^f_{ap} \leqslant \sum_{p'=p}^{p+\Delta p^f} W^c_{ap'} \quad \forall a, p \in \cup_v ICA_v \tag{30}$$

If CA chamber a is closed at period p, it must remain closed for at least Δp^c time periods, then the following logical implication must be true:

$$W^c_{ap} \Rightarrow \left(\neg W^o_{ap} \wedge \neg W^o_{a,p+1} \wedge \ldots \wedge \neg W^o_{a,p+\Delta p^c}\right) \tag{31.a}$$

which can be transformed into the following inequalities:

$$W^c_{ap} + W^o_{ap'} \leqslant 1 \quad \forall a, p \in \cup_v ICA_v, p' \in \cup_v OCA_v, p \leqslant p' \leqslant p + \Delta p^c \tag{31}$$

Moreover, if CA chamber a is closed in period p, it has to be opened at any period after Δp^c time periods.

$$W^c_{ap} \Rightarrow \left(W^o_{a,p+\Delta p^c+1} \vee \ldots \vee W^o_{a,P}\right) \tag{32.a}$$

This logical relation is enforced by the following inequality:

$$W^c_{ap} \leqslant \sum_{p' \geqslant p+\Delta p^c+1}^{P} W^o_{ap'} \quad \forall a, p \in \cup_v ICA_v \tag{32}$$

Finally, if CA chamber a is opened in period p, it has to be emptied in at most Δp^e time periods. The corresponding logic propositions and constraints can be written as follows:

$$W^o_{ap} \Rightarrow \left(W^e_{ap} \vee W^e_{a,p+1} \vee \ldots \vee W^e_{a,p+\Delta p^e}\right) \tag{33.a}$$

$$W^o_{ap} \leqslant \sum_{p'=p}^{p+\Delta p^e} W^e_{ap'} \quad \forall a, p \in \cup_v OCA_v \tag{33}$$

The logic propositions (34.a)–(37.a) are posed to establish the sequence of stages. If chamber a has not initiated the filling process before period p, then it cannot be closed in those periods.

$$\left(\neg W^f_{a1} \wedge \neg W^f_{a2} \wedge \ldots \wedge \neg W^f_{ap}\right) \Rightarrow \left(\neg W^c_{a1} \wedge \neg W^c_{a2} \wedge \ldots \wedge W^c_{ap}\right) \tag{34.a}$$

$$\sum_{p' \leqslant p} W^f_{ap'} \geqslant \sum_{p' \leqslant p} W^c_{ap'} \quad \forall a, p \in \cup_v ICA_v \tag{34}$$

If chamber a has not been closed until period p, then it cannot be opened before at least Δp^c periods from p.

$$\left(\neg W^c_{a1} \wedge \neg W^c_{a2} \wedge \ldots \wedge \neg W^c_{ap}\right) \Rightarrow \left(\neg W^o_{a1} \wedge \neg W^o_{a2} \wedge \ldots \wedge W^o_{a,p+\Delta p^c}\right) \tag{35.a}$$

$$\sum_{p' \leqslant p} W^c_{ap'} \geqslant \sum_{p' \leqslant p+\Delta p^c} W^o_{ap'} \quad \forall a, p \in \cup_v ICA_v \tag{35}$$

Similarly, if a CA chamber a has not been opened up to time period p, then it cannot be emptied.

$$\left(\neg W^o_{a1} \wedge \neg W^o_{a2} \wedge \ldots \wedge \neg W^o_{ap}\right) \Rightarrow \left(\neg W^e_{a1} \wedge \neg W^e_{a2} \wedge \ldots \wedge W^e_{ap}\right) \tag{36.a}$$

$$\sum_{p' \leqslant p} W^o_{ap'} \geqslant \sum_{p' \leqslant p} W^e_{ap'} \quad \forall a, p \in \cup_v OCA_v \tag{36}$$

In order to avoid solutions with the same optimal value for the objective function, logical proposition (37) is posed. It establishes that available CA chambers are utilized in ascending numerical order.

$$W^f_{ap} \Rightarrow \left(W^f_{a-1,1} \vee W^f_{a-1,2} \vee \ldots \vee W^f_{a-1,p}\right) \tag{37.a}$$

Then, the following constraint establishes that chamber a is used only if unit $a-1$ has been already assigned.

$$W^f_{ap} \leqslant \sum_{p' \leqslant p} W^f_{a-1,p'} \quad \forall a > 1, p \in \cup_v ICA_v \tag{37}$$

CA chamber a may not be used at all; in other words, it is not a mandatory requirement to use all CA chambers.

$$\sum_{p \in \cup_v ICA_v} W^f_{ap} \leqslant 1 \quad \forall a \tag{38}$$

Conversely, if chamber a is going to be used ($\sum_{p \in \cup_v ICA_v} W^f_{ap} = 1$), it has to be closed, remain in that state during the minimum period and then opened in some period of the planning horizon.

$$\sum_{p \in \cup_v ICA_v} W^c_{ap} = \sum_{p \in \cup_v ICA_v} W^f_{ap} \quad \forall a \tag{39}$$

$$\sum_{p \in \cup_v OCA_v} W^o_{ap} = \sum_{p \in \cup_v ICA_v} W^f_{ap} \quad \forall a \tag{40}$$

$$\sum_{p \in \cup_v OCA_v} W^e_{ap} = \sum_{p \in \cup_v ICA_v} W^f_{ap} \quad \forall a \tag{41}$$

All the discussed up to this point is related to the operations of CA storage. The posed propositions generate integer cuts on binary variables for representing the way the chambers work. At this point, additional variables shown in Fig. 2, $Y^{(\bullet)}_{ap}$, are defined to represent the five stages involved in CA chambers operations. These variables are related to binary variables $W^{(\bullet)}_{ap}$ and can be treated as a continuous in the interval $[0,1]$.

In Eq. (42) variable Y^w_{ap} takes value 1 when the CA chamber is empty and available for being used. It takes a null value in that period when the chamber starts to be filled ($W^f_{ap} = 1$).

$$Y^w_{ap} = Y^w_{a,p-1} - W^f_{ap'} + 1|_{p=\min(IEV_v)-1} \quad \forall a, p' \in \cup_v ICA_v, p \in \cup_v HS_v \tag{42}$$

Variable Y^f_{ap} is related to the filling stage of chamber a and is equal to 1 when it begins to be filled, up to the period when it is closed ($W^c_{ap} = 1$)

$$Y^f_{ap} = Y^f_{a,p-1} + W^f_{ap} - W^c_{a,p-1} \quad \forall a, p > \min_v(IEV_v), p \in \cup_v ICA_v \tag{43}$$

Once the cooling chamber is closed, variable Y^c_{ap} takes value 1 for those periods before the one it is opened ($W^o_{ap} = 1$).

$$Y^c_{ap} = Y^c_{a,p-1} - W^c_{ap''} - W^o_{ap'} \quad \forall a, p > \min_v(IEV_v), \\ p'' \in \cup_v ICA_v, p' \in \cup_v OCA_v, p \in \cup_v HS_v \tag{44}$$

The emptying stage is bounded by the period when the chamber is opened and that when there is no more fruit inside the chamber ($W^e_{ap} = 1$).

$$Y^p_{ap} = Y^p_{a,p-1} - W^o_{ap} - W^e_{a,p-1} \quad \forall a, p \in \cup_v OCA_v \tag{45}$$

Finally, variable Y^e_{ap} is equal to 1 for those periods when there is no fruit inside the CA chamber.

$$Y^e_{ap} = Y^e_{a,p-1} + W^e_{ap} \quad \forall a, p \in \cup_v OCA_v \tag{46}$$

At each time period p, only one operation (i.e., waiting, filling, closing, opening, or emptying) can be performed (Fig. 2).

$$Y^w_{ap} + Y^f_{ap''} + Y^c_{ap} + Y^p_{ap'} + Y^e_{ap'} = 1 \\ \forall a, p'' \in \cup_v ICA_v, p' \in \cup_v OCA_v, p \in \cup_v HS_v \tag{47}$$

The stock of fruit v in chamber a at the end of a time period p, S^a_{aqvp}, depends on the amount stored in the previous period, $S^a_{aqv,p-1}$; the incoming fruit during period p, $PFCA_{aqvp}$; and the extraction for commercialization, CAS_{aqvp}. It is worth highlighting that according to operation logics, the periods when fruit enters the chamber do not coincide with those when fruit leave it ($ICA_v \cap OCA_v = \varnothing$).

$$S^a_{aqvp} = S^a_{aqv,p-1} + PFCA_{aqvp''} - CAS_{aqvp'} \\ \forall a, q, v, p'' \in ICA_v, p' \in OCA_v, p \in HS_v \tag{48}$$

Taking into account that only one kind of fruit must be kept into the CA chamber, an additional binary variable U_{ae} is introduced, which takes value 1 if chamber a is selected to store fruit e and 0 otherwise. Then,

$$\sum_q \sum_{v \in EV_e} S^a_{aqvp} \leqslant S^{aUB}_{ae} U_{ae} \quad \forall a, e, p \in HS'_e \tag{49}$$

$$\sum_e U_{ae} = \sum_{p \in \cup_v ICA_v} W^f_{ap} \quad \forall a \tag{50}$$

Inequality (51) expresses that if chamber a is empty at period p ($Y^e_{ap} = 1$) then the amount of fruit inside it has to be null.

$$\sum_q \sum_v S^a_{aqvp} \leqslant BM(1 - Y^e_{ap}) \quad \forall a, p \in \cup_v OCA_v \tag{51}$$

When a chamber a closes ($W_{ap}^{c} = 1$), the amount of fruit inside it has to be greater than a minimum value which is expressed as a percentage fa of its maximum capacity ($fa = 75\%$).

$$\sum_q \sum_v S_{aqvp}^{a} \geqslant fa \ \min_e \{S_{ae}^{aUB}\} W_{ap}^{c} \quad \forall a, p \in \cup_v ICA_v \tag{52}$$

If fruit variety v is stored in unit a, the following inequalities limit the incoming amount $PFCA_{aqvp}$ between minimum and maximum filling rates:

$$\sum_q \sum_v PFCA_{aqvp} \geqslant F_p^{inLB} Y_{ap}^{f} \quad \forall a, p \in \cup_v ICA_v \tag{53}$$

$$\sum_q \sum_v PFCA_{aqvp} \leqslant F_p^{inUB} Y_{ap}^{f} \quad \forall a, p \in \cup_v ICA_v \tag{54}$$

Similarly, Eqs. (55) and (56) set the limits for fruit leaving the chamber a.

$$\sum_q \sum_v CAS_{aqvp} \geqslant F_p^{outLB} Y_{ap}^{p} \quad \forall a, p \in \cup_v OCA_v \tag{55}$$

$$\sum_q \sum_v CAS_{aqvp} \leqslant F_p^{outUB} Y_{ap}^{p} \quad \forall a, p \in \cup_v OCA_v \tag{56}$$

The material that entered into a CA chamber must leave it at some period of the planning horizon.

$$\sum_{p \in ICA_v} PFCA_{aqvp} = \sum_{p \in OCA_v} CAS_{aqvp} \quad \forall a, q, v \tag{57}$$

3.4. Commercialization

Constraints (58) are concerned with the total tradable fruit over all the markets at period p ($\sum_m SM_{mqvp}$), which is the sum of the quantities leaving the packaging lines delivered directly to customers PFS_{qvp} plus the amounts coming from both kinds of refrigerated storage (CSS_{cqvp} and CAS_{aqvp}).

$$PFS_{qvp'} + \sum_c CSS_{cqvp'} + \sum_a CAS_{aqvp''} = \sum_m SM_{mqvp}$$
$$\forall q \in AQ_m, v \in AV_m, p' \in HCS_v, p'' \in OCA_v, p \in HS_v \tag{58}$$

The quantity of land transport is bounded by the number of trucks available for every market, NT_{mp}^{UB}. In addition, trucks have different load capacities according to destiny, TC_m.

$$\sum_{q \in AQ_m} \sum_{v \in AV_m} SM_{mqvp} \leqslant TC_m NT_{mp}^{UB} \quad \forall m, p \in \cup_v HS_v \tag{59}$$

Fruit for overseas clients (i.e., $m = 1$) should be sent to some port h. Note that only first-quality fruit is accepted by this market. This is expressed by Eq. (60).

$$SM_{mqvp} = \sum_h SM_{hvp}^{h} \quad \forall m = 1, q = 1, v \in AV_m, p \in HS_v \tag{60}$$

The fruit for overseas clients dispatched from packaging plant to port h in period p, SM_{hvp}^{h}, is given by the sum of the amount held in cold storage at the port, SO_{hvp}^{hc}, and the quantity directly loaded onto ship b, SO_{hbvp}^{hb} if being at the port h. This last condition is controlled by set EPS_{bh}, which is formed by the periods when the ship is at port. Parameters ETA_{bh} and ETD_{bh} define the corresponding time window.

$$SM_{hvp}^{h} = SO_{hvp}^{hc} + \sum_b SO_{hbvp'}^{hb} \quad \forall h, v \in AV_{m_1}, p \in OH_{vh}, p' \in EPS_{bh} \tag{61}$$

In constraint (62), the amount of fruit stored in the port h at the end of period p, S_{hvp}^{hc}, depends on the stock at the previous time period, $S_{hv,p-1}^{hc}$, the net amount incoming during this period, SO_{hvp}^{hc}, and the amount upload to the vessel b, SO_{hbvp}^{cb}, as follows:

$$S_{hvp}^{hc} = S_{hv,p-1}^{hc} + SO_{hvp}^{hc} - \sum_b SO_{hbvp'}^{cb} \quad \forall h, v \in AV_{m_1}, p \in OH_{vh}, p' \in EPS_{bh} \tag{62}$$

Constraint (63) models the low temperature storage capacity of port h denoted by S_h^{hcUB}.

$$\sum_{v \in AV_{m_1}} S_{hvp}^{hc} \leqslant S_h^{hcUB} \quad \forall h, p \in \cup_v OH_{vh} \tag{63}$$

All fruit entering port h must be dispatched in some ship b along the planning horizon.

$$\sum_{p \in OH_{vh}} SO_{hvp}^{hc} = \sum_{p \in EPS_{bh}} \sum_b SO_{hbvp}^{cb} \quad \forall h, v \in AV_{m_1} \tag{64}$$

Besides, the stocking levels of fruit v on the ship b at period p, S_{bvp}^{b} is equal to the level of the preceding period, $S_{bv,p-1}^{b}$, plus the incoming amounts from both: cold storage at port, SO_{hbvp}^{cb}, and directly loaded from trucks arriving from packaging plants or other storage facilities, SO_{hbvp}^{hb}. Each vessel b can be loaded with fruit at different ports, therefore:

$$S_{bvp}^{b} = S_{bv,p-1}^{b} + \sum_h \left(SO_{hbvp}^{cb} + SO_{hbvp}^{hb} \right) \quad \forall b, v \in AV_{m_1}, p \in \cup_h EPS_{bh} \tag{65}$$

Finally, the marketable fruit sent to overseas market is calculated in Eq. (66) while Eq. (67) determines the amounts for regional and local markets.

$$SS_{dvp} = \sum_{b \in SR_d} S_{bvp'}^{b} \quad \forall d \in SD_{m_1}, v \in AV_{m_1}, p' = \max_h \{ETD_{bh}\}, p \in HS_v \tag{66}$$

$$SS_{dvp} = \sum_{q \in AQ_m} SM_{mqvp} \quad \forall m > 1, d \in SD_m, v \in AV_m, p \in HS_v \tag{67}$$

3.5. Objective functions

In this study, two evaluation criteria have been considered to measure the system performance. The first one, expressed in Eq. (69), consists in minimizing the total negative deviations of sales Δ^- with respect to the given demand profiles, S_{dep}^{T}. This deviation is expressed as the sum of fruit shortage, ΔS_{dep}^{T-}, defined in Eq. (68).

$$\sum_{v \in (AV_m \wedge EV_e)} SS_{dvp} = S_{dep}^{T} + \Delta S_{dep}^{T+} - \Delta S_{dep}^{T-} \quad \forall d \in SD_m, e, p \in \cup_v HS_v \tag{68}$$

$$\text{Min } \Delta^- = \sum_{p \in \cup_v HS_v} \sum_d \sum_e \Delta S_{dep}^{T-} \tag{69}$$

The second objective function in Eq. (70), to be maximized, is the total profit determined by the difference between incomes from selling both, packaged fruit and out of specification fruit (for juice production), and total costs which is made up of seven components. The first cost element has to do with raw materials and comprehends expenditures incurred in production at own farms and purchasing fruit from third-party suppliers. The next cost element comprises the expenses at packaging lines which are conformed by two terms: the processing cost dependent on the type of package used and on the labor cost, which depends on the number of hired shifts. The third term corresponds to the depreciation cost which comprises a fixed term associated to building and equipment and a variable component due to the depreciation of the bins. The fourth and fifth cost elements account for the fixed and variable costs associated with CS and CA cold storage, respectively. The sixth element models the expenses due to transportation among the nodes of the chain. The next term is the inventory cost of stored fruit in refrigerated facilities at port. Ultimately, the last term is the overhead cost evaluated as a function of the tradable volume of fruit that includes general administrative expenses and other minor items not considered in previous terms.

$$
\begin{aligned}
\text{Max}\, BEN = & \sum_{p\in\cup_v HS_v}\sum_{d}\sum\sum_{e}(\phi_{dep}SS_{dep} + \phi_e^w(D_{ep} + WT_{ep})) \\
& - \sum_{p\in\cup_v HP_v}\sum_{v}(c_v^{pp}PP_{vp} + c_v^{p3s}F3s_{vp}) \\
& - \sum_{p\in\cup_v HS_v}\left(\sum_{m}\sum_{e}\sum_{q\in AQ_m}\sum_{\substack{v\in AV_m \\ v\in EV_e}} c_{me}^{pack}SM_{mqvp} + \sum_{s}(c_s^{mp}Z_{sp})H_p\right) \\
& - \left(fc^{dep} + \sum_{p\in\cup_v HCS_v}\sum_{e}\sum_{l}\sum_{q}\sum_{v\in EV_e} vc_e^{dep}PF_{lqvp}\right) \\
& - \sum_{p\in\cup_v HCS_v}\left(\sum_{e}\sum_{c}\sum_{v\in EV_e} c_e^c\left(S_{cvp}^{fnp} + \sum_{q} S_{cqvp}^{fp}\right)H_p + \sum_{c} fcV_{cp}H_p\right) \\
& - \sum_{p\in\cup_v HS_v}\left(\sum_{e}\sum_{a}\sum_{q}\sum_{v\in EV_e} c_{eq}^a S_{aqvp}^a H_p + \sum_{a} fc\left(Y_{ap}^f + Y_{ap}^c + Y_{ap}^p\right)H_p\right) \\
& - \sum_{p\in\cup_v HS_v}\sum_{e}\sum_{m}\sum_{q\in AQ_m}\sum_{v\in EV_e} c_{me}^{\log}SM_{mqvp} + \sum_{p\in\cup_v OH_{vh}}\sum_{h}\sum_{v} c_h^{hc}S_{hvp}^{hc}H_p \\
& - \sum_{p\in\cup_v HS_v}\sum_{m}\sum_{q\in AQ_m}\sum_{v\in AV_m} c^{ov}SM_{mqvp}
\end{aligned} \tag{70}
$$

3.6. Methodology

A tradeoff exists between the previous objective functions because client dissatisfaction is minimized at the expense of total profit reductions. This basically occurs because many good selling opportunities along the year have to be missed in order to save fruit to avoid product delivery shortage in the future.

In order to quantify such tradeoff, the lexicographic method is used in this work to address the described bi-objective optimization problem. This approach consists in defining the priority order between the objective functions and then performing a sequence of single objective optimization where the optimal value of the first objective function is added as a constraint in the following problem. In our work, the minimization of the clients dissatisfaction has the highest priority, thus the first step consist in solving problem (P1) given by the minimization of Eq. (69) subject to constraints (1)–(68). Afterward, problem (P2) is solved aimed at maximizing Eq. (70) subject to constraints (1)–(68) and an additional restriction $\Delta^- = \Delta^{-*}$.

4. Case studies

In this section, the capability of the proposed approach in dealing with planning decisions is investigated through the solution of different scenarios assessing modifications in the SC structure. Here, various structures are posed intending to determine the level of adaptation of the fruit SC to the demand profiles and also to estimate how its profitability is affected. This study is carried out by performing variations on diverse capacities into the SC. First, the refrigerated storage capacity is modified by increasing the number of CS chambers from 1 to 5 and the number of CA chambers from 1 to 6, resulting in a total of 30 scenarios. Next, the packaging capacity is analyzed by changing the number of processing lines *PL* from 1 to 4. Finally, the impact of the change in the transport capacity is addressed by varying the number of available trucks per day from 1 to 7.

A base case SC is solved in the first place to establish a reference frame. In this example the SC handles two fruit species, i.e. apples and pears, with four varieties per species, apples: Red Delicious, Gala, Granny Smith, Cripp's Pink; pears: Williams', Packham's Triumph, Beurré D'Anjou, Abate Fetel, typical from the region under study. The discretization of the 1 year horizon time was performed as described in Section 2.5 resulting in 34 planning periods (details shown in Appendix A).

In the packaging plant there exist two processing lines (i.e. *PL* = 2) with the possibility of hiring up to three shifts in each time period for a minimum of a 15 days period each. As mentioned earlier, there are three fruit qualities under consideration in the SC, and refrigeration is provided by two CS chambers and three CA storage units.

Fruit sales are divided between five diverse destinations, the first three correspond to the overseas market (EU, Russia, and USA), plus Brazil and the local market. Only one port is considered for dispatching the fruit to overseas clients. Moreover, four trucks per day are available to perform the transport of goods to the port and to local and regional markets. The remaining data and parameters for solving the examples are provided in Appendix A. The reported data was taken from annual report "Anuario Estadístico 2011 de Egreso de Peras y Manzanas de la Región Protegida Patagónica" Funbapa (2012) and information provided by producers and institutions from "Alto Valle de Río Negro y Neuquén" Argentine region.

All the examples were implemented and solved using GAMS (Brooke et al., 2012) version 23.0 on an Intel@*Core*™ 2 Quad Q8200, 2.33 GHz processor (2.96 GB of RAM) and CPLEX 11.2 was used for solving the MILP problems with a 1% integrality gap.

5. Results and discussion

Table 1 shows the statistics for the base-case problem whereas Table 2 displays the variation in the number of equations and variables when changes in capacities are carried out. Thus, ±*CA* refers to the variation of ±1 in the amount of CA chambers, ±*CS* denotes a fluctuation of ±1 in the number of CS chambers, ±*PL* imply that the maximum number of lines is modified ±1, and ±Tr indicates a change of ±1 in the available transport capacity.

As can be seen in Table 2, the last case does not present any changes in the problem size because it only affects parameter NT_{mp}^{UB} in Eq. (59) instead of elements in sets as occurs in the others cases. With regard to the CPU time, for the base-case model P1 was solved in 1859 CPU seconds whereas the optimal solution of model P2 was found in 342 CPU seconds.

5.1. Variation in the number of CS and CA chambers

Table 3 reports the client dissatisfaction in percentage for the 30 scenarios generated when the cold storage structure is changed.

Table 1
Base case: problem size.

Equations	10,367
Continuous variables	12,724
Binary variables	549

Table 2
Variations in the problem size with changes on capacities.

	±*CA*	±*CS*	±*PL*	±Tr
Equations	1446	620	699	0
Continuous variables	1471	1298	636	0
Binary variables	47	98	106	0

Table 3
Demand violation [%].

CS	Number of CA chambers, *CA*					
	1	2	3	4	5	6
1	33.9	28.6	24.6	22.8	18.6	16.0
2	25.4	20.0	15.2	12.4	9.3	6.8
3	25.4	20.0	15.1	10.9	8.3	5.8
4	25.4	20.0	15.1	10.9	8.3	5.8
5	25.4	20.0	15.1	10.9	8.3	5.8

Table 4
Benefits [$\times 10^6$ $].

CS	Number of CA chambers, *CA*					
	1	2	3	4	5	6
1	3.4	2.7	1.6	2.6	1.3	1.2
2	3.9	3.1	1.5	2.3	1.1	0.9
3	4.6	3.9	3.0	2.2	1.8	1.9
4	5.0	4.4	3.6	2.9	2.7	2.5
5	5.4	4.7	4.0	3.4	3.1	3.1

The optimal profits for the corresponding minimum dissatisfaction are presented in Table 4.

As seen in Table 3, for a given number of CA chambers, the increase from 1 to 2 CS units always diminishes significantly the demand violation. In some cases, an additional reduction is achieved with 3 CS chambers, but beyond this value, unattended demand remains the same. This behavior is explained because the fruit can be stored in a CS chamber during a relative short period only. Since in the first part of the year the demand is mostly fulfilled with fruit coming directly from the packing lines, most client dissatisfaction corresponds to the second half of the year when CS chambers has minimum impact. Conversely, since CA chambers are employed for keeping packaged fruit during long periods, whenever its number augments, a progressive reduction in the demand violation is accomplished because they permit meeting demands far in the time horizon.

In general, the levels of achieved profitability for the different configurations (see Table 4) increase with the number of CS and abate with the amount of CA units. Nevertheless, in some cases the benefit decreases with the quantity of CS chambers, since it is necessary to resign sales in the present with high profit margin in order to reduce the level of client dissatisfaction in the future. On the other hand, as the number of CA chambers grows, the system is able to meet more demand during the second half of the year, sacrificing sales with higher profit margin in the first half and increasing fruit conservation costs.

In Fig. 5a, the total processed fruit is shown for all considered storage capacities. It can be seen that in all the cases the amount of processed fruit does not change with the number of CA chambers, whilst it increases with the number of CS because this value permits an indirect rise in the packaging plant capacity allowing the temporary storage of fruit before being sent to the classification lines. In other words, for a given processing capacity defined by a number of classification lines, an increase in conventional cold storage capacity allows an extended processing period.

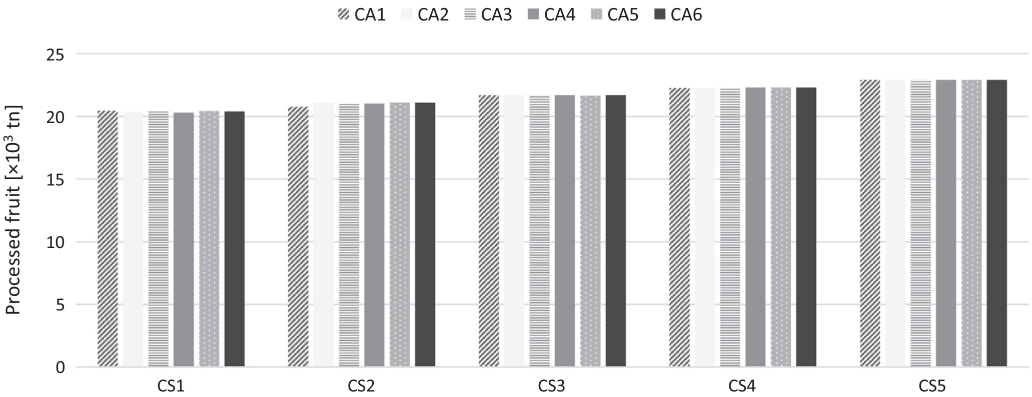
Fig. 5b and c illustrates how the fruit processing (classification) per variety fluctuates when the number of CS and CA chambers increases, respectively. The quantity of chambers given in the base case was taken as reference, i.e. 3 chamber for CA (Fig. 5b) and 2 for CS (Fig. 5c). When the number of CS units increases (Fig. 5b), there exists a larger participation of those varieties that are more profitable in the first part of the year (see Appendix Figs. A2–A6). Thus, the produced volume of fruit varieties v_1, v_4, v_5, and v_8 increases at the expense of v_3, v_6 and v_7. Otherwise, Fig. 5c shows that adjustments are made in order to satisfy the demand profile of the second part of the year with the aid of additional CA chambers. For example, the processed amount of v_1, v_3, and v_6 increases, forcing a reduction in the production of v_4 and v_5 as the number of CA chambers augments. Varieties v_1 and v_3 correspond to fruits required by domestic and regional markets (only v_1 for Brazil) along the whole year. The increment in variety v_6 is caused by the higher preference of this fruit for the local market in the second part of the year due to its excellent conservation properties compared with other pear varieties. Also, it is observed that fruit variety v_2 does not show substantial alteration in either case.

5.2. Variation in the number of packaging lines

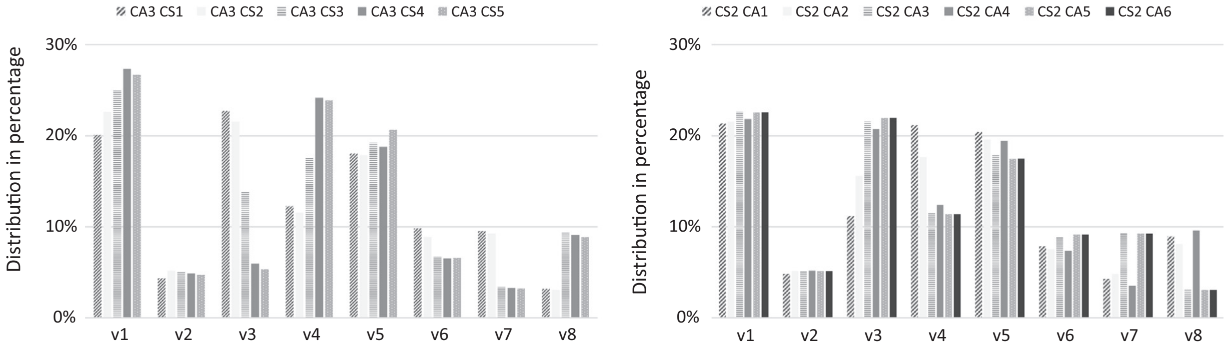
Fig. 6 shows some general results for the four scenarios generated when modifications in the number of classification lines are considered in the system ($PL = 1$–4). In Fig. 6a the total profit of the business (BEN) together with the level of supply shortage (Dif-) are illustrated. Fig. 6b and c presents the total volume of processed fruit and the distribution per variety, respectively. Fig. 6d shows the utilization patterns for the different cold storage options.

Note that the level of satisfaction shortage is affected primarily when a transition occurs from one to two processing lines (Fig. 6a). Beyond this value, no improvement is observed on this parameter. However, the economic benefit shows a sustained rise as the processing capacity increases in all scenarios. It can be noted that, when the packaging plant has only one classification line, no positive return is obtained.

As expected, the amount of processed fruit augments with the number of packaging lines (Fig. 6b). Such increment is attained thanks to the fruit from third party suppliers. However, no significant increase is observed with an increment from 3 to 4 lines, which indicates the presence of a "bottleneck" in the system that prevents the processing of a larger amount of fruit. In this case, the bottleneck is attributed to the upper bound on the amount of fresh fruit that can be received per day, related to constrained upstream resources (Eq. (10)). Regarding the use of cold storage (Fig. 6d), a drop in the stock of cold non-processed fruit in CS chambers is observed as the number of lines increments. The greater processing capacity allows reducing the amount of fruit in stock before being processed and also avoiding the undesirable refrigeration of out-of standard fruit. The quantities of processed fruit either in CA or CS chambers remain practically invariant



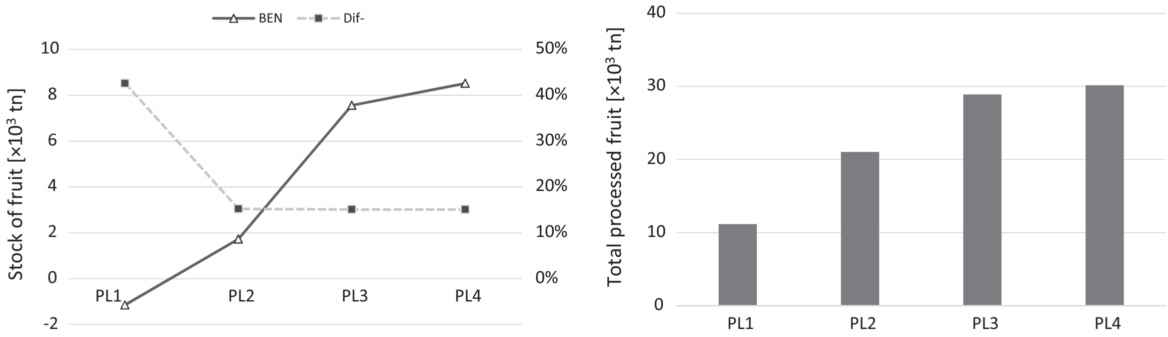
(a) Total processed fruit



(b) Distribution of fruit varieties: $CA = 3$, $CS = 1\text{-}5$

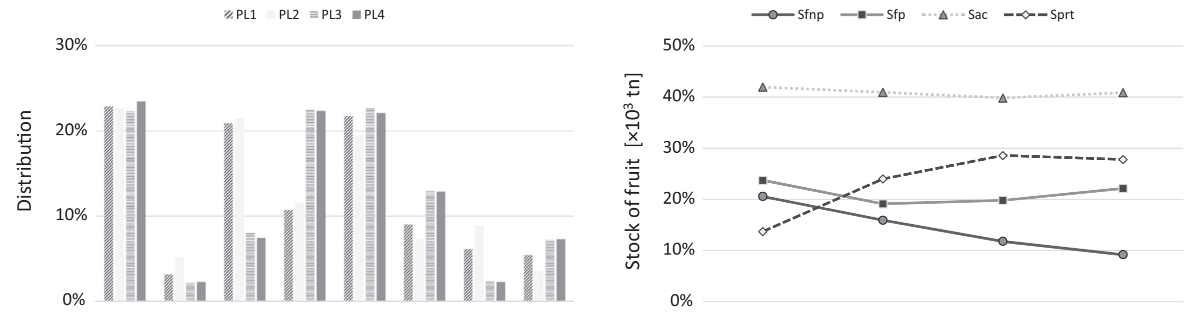
(c) Distribution of fruit varieties: $CS = 2$, $CA = 1\text{-}6$

Fig. 5. Total volume of processed fruit and distribution of fruit variety for different scenarios.



(a) Benefit and demand violation for: $PL = 1 - 4$.

(b) Total processed fruit for $PL = 1 - 4$.



(c) Distribution per variety for $PL = 1 - 4$.

(d) Utilization of different cold storage for $PL = 1 - 4$.

Fig. 6. Obtained results when the number of classification lines is changed.

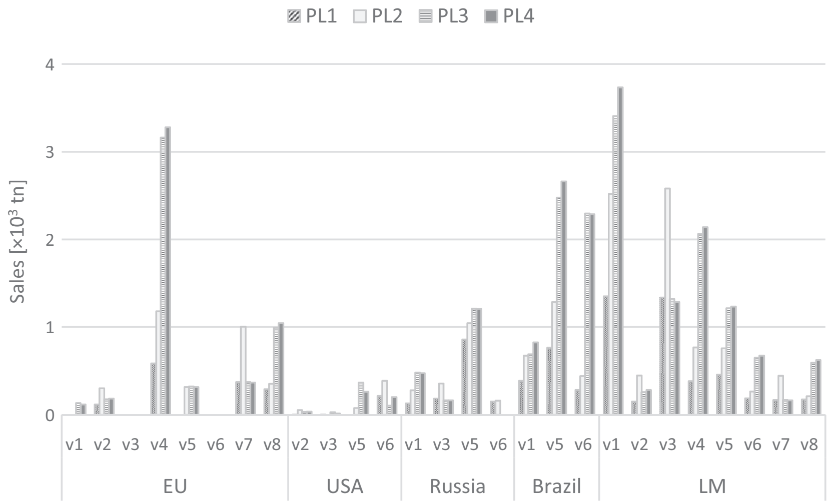
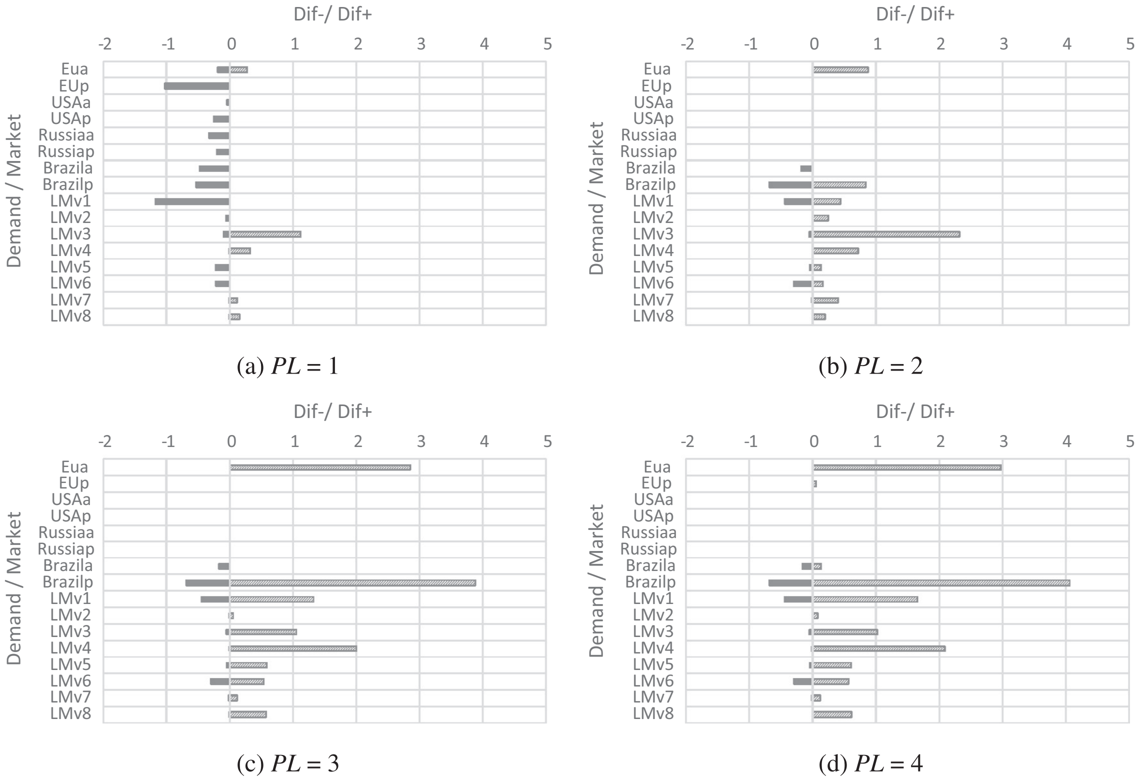


Fig. 7. Production per variety sold in each market for different number of packaging lines.



(a) $PL = 1$

(b) $PL = 2$

(c) $PL = 3$

(d) $PL = 4$

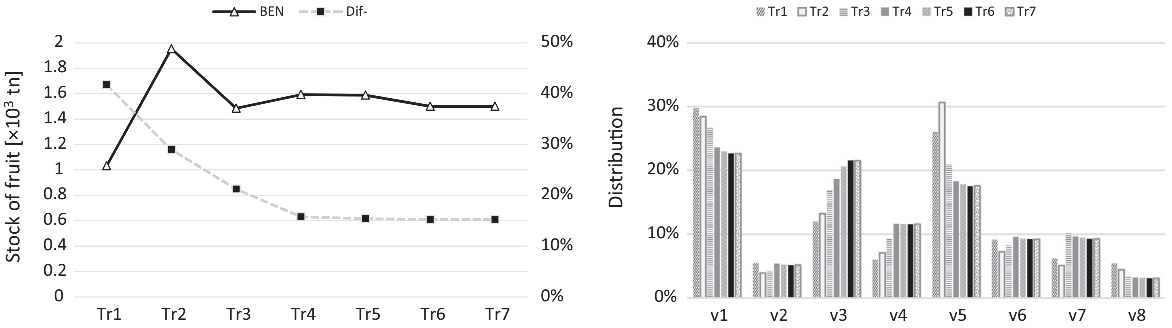
Fig. 8. Positive and negative deviations respect to demand profiles for different number of packaging lines.

whereas the accumulation of inventory at ports presents a remarkable increment, which leads to higher fruit volumes sold to overseas clients.

Fig. 7 illustrates the volumes of packed fruit per variety traded to each market, whereas Fig. 8 shows both positive and negative deviations respect to the given demand profiles for the analyzed scenarios. In general, an increment in processing capacity always increases the amounts of all fruit varieties traded to all markets (Fig. 7). It should be remarked that from 2 packaging lines on the system, there exists a noteworthy fall in the in supply shortage. Moreover, surpluses are even observed especially for apples sold to EU, pears to Brazil, and varieties v_1 and v_3 in the local market (see Fig. 8).

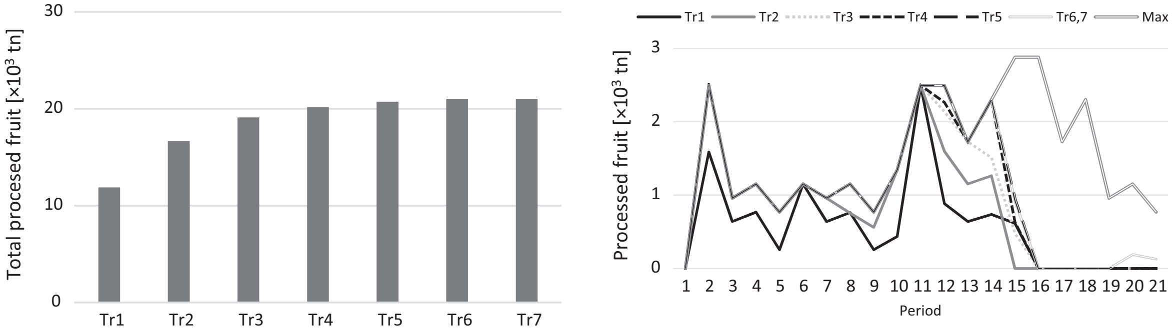
5.3. Transportation capacity

In this last case, a study over the availability of trucks for transporting packed fruit within the SC is carried out. Recall that this discrete parameter is approximated as a continuous capacity in the model. Fig. 9 summarizes the results for the seven transport capacity scenarios. It should be noted that the maximum capacities of the system (transportation, storage, processing) vary at each time period since each period has different lengths in days. It can be seen from Fig. 9a that the supply shortage shows a sustained declining trend until the number of daily trucks reaches the value of 4, after that the variation is less than 1%. Moreover, the profit curve presents a less intuitive behavior. For example, increasing



(a) Benefit and demand violation for $Tr = 1 - 7$.

(b) Distribution per variety for $Tr = 1 - 7$.



(c) Total processed fruit for $Tr = 1 - 7$.

(d) Processed fruit in each period for $Tr = 1 - 7$.

Fig. 9. Obtained results when the number of daily trucks is changed.

the number of trucks from 1 to 2 produces a significant increase in benefit. This is basically explained because the rise in transportation allows a significant increase in fruit delivery. However, increasing from 2 to 3 trucks per day produces a reduction in benefit. This behavior has to do with the fact that since the benefit is the subordinated objective, the increased transportation capacity is preferably used to minimize the supply shortage (leading objective) instead of trading fruit of higher value.

Fig. 9c shows that the volume of processed fruit increases with an increase in the number of daily trucks. However, for 5 and more trucks per day, no significant improvements are detected. It is worth highlighting that for the first scenario, only in period 6 the system works at full capacity (Fig. 9d). For the second scenario (i.e. 2 trucks per day) full capacity is reached at time periods 7, 10, and 11. Finally, from 5 trucks per day the system works at maximum capacity along the whole harvest season.

6. Conclusions and future work

In this work, a new formulation for the mid-term SC planning problem in the pome fruit industry explicitly accounting for the detailed operation of CS, CA and cold facilities at ports was proposed. The problem was formulated as a multi-period MILP model and the lexicographic approach was adopted to handle the multi-objective optimization nature of the business. Specifically, the influence of changes in the SC structure on client dissatisfaction as well as on profit was investigated. An increment in the demand satisfaction produced, in general, a reduction of the benefit, reflecting a conflictive relationship between these two objectives.

Basically, client dissatisfaction is minimized at the expense of total profit reductions because many good selling opportunities along the year are missed in order to save fruit to avoid product delivery shortage in the future. This can be sought as an expected behavior for these two naturally opposite objectives; however, the model is able to quantitatively weigh both criteria under different scenarios in a highly complex system.

In the studied cases, client dissatisfaction presents a point over which additional increments in the resource (storage, production, transportation) does not produce significant improvements. This is explained in part by the seasonal nature of this activity. Conversely, the variations observed in the total profits for the different analyzed scenarios are the result of two effects: (i) the influence of increased capacity of a specific resource; (ii) the level of demand satisfaction, which is the adopted leading objective.

The obtained results suggest that the developed model constitutes a valuable tool to investigate such a complex system from a tactical viewpoint. In this sense, the type of studies performed in this work might help to design the infrastructure of the network before the start of business season. A valuable tactical result related with infrastructural decisions that can be obtained with the present model has to do with the estimation of the amount of cold storage required for safe operation along the season. Although the company possesses own cold storage facilities, it will need to hire additional capacity from third party providers if required. A similar analysis can be done on port storage availability, which has to be negotiated before the ships arrival with the port operators. Finally, transportation volumes within the network has also to be estimated since, although large companies use to have their own fleet of trucks, supplementary transportation is often contracted out.

A further challenge, currently under analysis, has to do with the actual implementation of the tactical decisions at the operational level. Due to the large uncertainty existing in practically every parameter of the system, in particular those related with fruit availability in farms and product prices, rolling horizon strategies are required to implement as close as possible the tactical solution without falling in infeasibilities. Moreover, such an approach is also required to deal with supply chain disruption episodes, such as processing and storage facilities out of service, which may interrupt the process for several days.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.compag.2016.10.008.

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