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Innovative Applications of O.R.

Optimizing tactical harvest planning for multiple fruit orchards using a metaheuristic modeling approach

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ABSTRACT

In a fruit harvest season, the fruit must be collected during a relatively short period of intense activity. Moreover, large fruit export companies commonly manage multiple orchards where the resources and labor are shared, making the decision process more complex. In this study, we address this harvest problem by proposing a mixed integer linear programming model for supporting tactical decisions during the harvest season in order to reduce total costs. This includes costs related to the fruit not reaching maturity and the number of harvest days. Due to the difficulty of solving this model optimally when real cases are considered, we developed a GRASP metaheuristic method. We compared the GRASP metaheuristic solution to the best integer solution obtained by an exact method using a real case. We observed that the metaheuristic produced a solution in less computational time than the best integer solution. The total costs obtained by the GRASP metaheuristic were two percent greater than the total cost obtained by the best integer solution. Additionally, we analyzed two scenarios to establish if the joint resource planning of the orchards would allow a cost reduction. The GRASP metaheuristic provides orchard managers with a harvest plan in a timely manner and adds greater flexibility to the decision process. The proposed model can be used to plan the harvesting of a variety of fresh fruits.

1. Introduction

The fresh fruit sector has grown significantly in recent years (FAO, 2014). This global growth is a result of the increasing demand from customers concerned about consuming healthier diets and obtaining fresh fruit all year round (Reynolds et al., 2014). This presents a challenge for fresh fruit supply chains (FSCs) that need to develop efficient coordination among all production steps in order to satisfy the increasing global demand. According to Soto-Silva et al. (2017), harvesting is one of the most important steps in the fresh FSC since it must be done in a relatively short period of intense activity. This task is complex because usually every fruit species and variety has a different ripening curve. The orchards usually plant several fruit species and varieties, which implies carrying out the respective harvests in different periods. For large fruit export companies, harvest planning decisions are even more complex because they need to plan the harvest for several orchards simultaneously. Currently, these companies often make harvest planning decisions based on the experience of farmers or orchard managers and usually face supply chain discoordination and fruit losses. Therefore, it is necessary to develop decision support tools for improving this decision-making process. Adding flexibility to the process is also essential for when unexpected changes during the harvest season occur. In this study, we focus on the development of decision support tools to improve tactical harvest planning when multiple orchards are considered. It is important to note that the tools proposed in this study also can be useful for the harvest planning of pome fruits (pears, apples, quinces, and medlars) and plums because their agricultural practices are very similar.

The development of optimization models for supporting decisions in the FSC began many decades ago. The study of Willis and Hanlon (1976) was the first to propose a mathematical programming model for making strategic planning decisions, aiming to select the optimal apple variety mix that should be planted. Years later, Caixeta-Filho (2006) presented a linear programming model for planning an orange harvest. The objective function of the model

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aimed to maximize a company's profits by considering logistics, soluble solids, and fruit acidity constraints. The model was applied in a Brazilian company for planning the harvest of 320 orchards. Masini et al. (2007) proposed a linear programming model for supporting tactical planning decisions of pome FSCs, such as pears and apples, assuming interactions among many operational nodes. The model sought to maximize profits in order to aid the negotiation of a company when clients and service providers' contracts needed to be established. Masini et al. (2008) proposed an operational planning framework for an industry FSC (pears and apples) based on a model predictive control algorithm. In the second step of this algorithm, an extension of the model developed by Masini et al. (2007) was implemented using binary variables. Catalá et al. (2013) developed a multi-period mixed integer linear programming (MILP) model that aimed to determine the optimal investment policy for an orchard along a time horizon under different financing scenarios. The model was used in a real case corresponding to an orchard of pears and apples located in Alto Valle del Rio Negro, Eastern Patagonia of Argentina. Jena and Poggi (2013) developed a mathematical model for supporting the tactical harvest planning decisions of sugar cane, seeking to maximize the total sugar content. The case study used by these authors had a planning horizon of seven months. In addition, an extension of this model was proposed by the authors in order to support operational decisions where a planning horizon from seven to 30 days could be considered. Soto-Silva et al. (2017) proposed three MILP models to optimize decisions about purchasing, transporting, and storing fresh produce. One model minimized the costs involved in fresh produce purchase; the second minimized the costs involved in fresh produce storage and the third model integrated the purchase and storage models into one model. These models were used in a case study representing an apple dehydration plant located in the Maule Region of Chile. Herrera-Cáceres et al. (2017) proposed a mixed integer linear model for planning an olive harvest. The model maximized the quantity of olive oil obtained, considering budget, plant capacity, and operational constraints. The authors considered the climatological phenomena during a harvest season through a model parameter (percentage of olives lost by climatological phenomena). The model was applied in a Chilean company and the obtained results that were better than the company's current practices, reaching an extraction increase of 4%. Jonkman et al. (2019) proposed a multi-objective modeling approach for optimizing agri-food industrial supply chains, considering seasonality in harvest decisions, perishability, and processing. In this way, the seasonality was incorporated as a maturity time window for each fresh product during the harvest period and the perishability was considered as an age index of the inventory during processing. The model aimed to maximize the total gross margin and minimize the global warming potential using the ε-constraint method. These authors presented different network configurations for a sugar beet supply chain according to the obtained Pareto-optimal solutions. These solutions had a better performance in the two analyzed criteria than the present solution of the case study.

Operations research (OR) models that support fresh fruit harvest decisions where the loss of fruit quality is considered explicitly in the objective function of the model are found in the works of Bohle et al. (2010) and González-Araya et al. (2015), Ferrer et al. (2008). Ferrer et al. (2008) presented a MILP model for scheduling harvest operations for wine grapes in order to minimize harvesting costs and fruit quality loss due to premature or delayed harvest. The proposed model sought to support decisions regarding routing, harvest scheduling, and labor allocation. Bohle et al. (2010) extended the model developed by Ferrer et al. (2008) by considering the uncertainties in harvesting productivity. The authors dealt with these uncertainties through a robust optimization model. González-Araya et al. (2015) developed a MILP model for aiding the tactical harvest planning of apple orchards, seeking to minimize harvesting costs. The objective function of this model included a penalty cost for harvesting fruit that did not meet export requirements. The model developed a harvest schedule that included the daily number of workers and bins that should be assigned to each block and the daily amount of fruit to be harvested.

A literature review of planning models in the agri-food supply chain is presented by Ahumada and Villalobos (2009); harvesting was included as one of the stages. Therefore, the authors also analyzed mathematical models devoted to supporting harvest decisions. Later, Soto-Silva et al. (2016) presented a literature review about OR models applied to fresh FSCs. In this review, the authors classified the models according to their purpose, decision level, analytical modeling approach, practical application, kind of fruit, country of the study, and novelty. These authors revised the mathematical models to support planting, harvesting, production, distribution, and inventory decisions. In the same year, Kusumastuti et al. (2016) presented a literature review about crop-related agri-chains, focusing on the integration of harvesting and processing planning and related inventory control issues. These authors observed that heuristic solution approaches should be considered in order to empirically apply the proposed models. In the literature, it is possible to find a few metaheuristic approaches for solving optimization models related to the agri-food supply chain (Cheraghalipour et al. 2019; Mogale et al. 2017; Musavi et al., 2017). These metaheuristic algorithms were developed to obtain solutions for large instances in a reasonable time. Musavi et al. (2017) used an adopted non-dominated sorting genetic algorithm-II (NSGA-II) for solving a sustainable hub-location-scheduling problem of a perishable food supply chain, which was formulated as a multi-objective optimization model. Mogale et al. (2017) developed an improved max-min ant system (IMMAS) and a max-min ant system (MMAS) for solving a non-linear mathematical model. This model aimed to optimize the tactical planning of a food grain supply chain. Cheraghalipour et al. (2019) analyzed five metaheuristics to solve a bi-level optimization model for the rice supply chain. The studied metaheuristics were genetic algorithm (GA), particle swarm optimization (PSO), two hybrid algorithms based on GA and PSO, and a modified GA that uses the movement formula of PSO (GPA). For a deeper understanding about solution methods for solving complex optimization models, it is possible to review the studies of Duan et al. (2018), Hoseini et al. (2018), Gharaei et al. (2019d), Gharaei et al. (2019a), Gharaei et al. (2019b), Gharaei et al. (2019c), among others.

To the best of our knowledge, there are no optimization models for supporting fruit tactical harvest planning that consider multiple orchards or farms. For large fruit export companies, it is a common practice to share resources during the tactical harvest planning of multiple orchards that produce different fruit species and varieties in order to satisfy market demands. With this in mind, this study presents the first mathematical model developed for planning the harvest of multiple orchards that share resources. The proposed model carries out a joint harvest planning of orchards that optimizes the use of resources. A Greedy Randomized Adaptive Search Procedure (GRASP) metaheuristic was developed due to the complexity of solving this model with exact methods in real cases (Resende & Ribeiro, 2014). In this way, the decision makers would obtain tactical harvest plans in a reasonable computational time.

This article is structured as follows. Section 2 describes the fruit harvest planning during a season. In Section 3, the proposed mathematical model for performing tactical harvest planning is presented. Section 4 details the GRASP metaheuristic developed for obtaining good quality solutions for the mathematical model. In Section 5, exact and metaheuristic solution methods are used in a

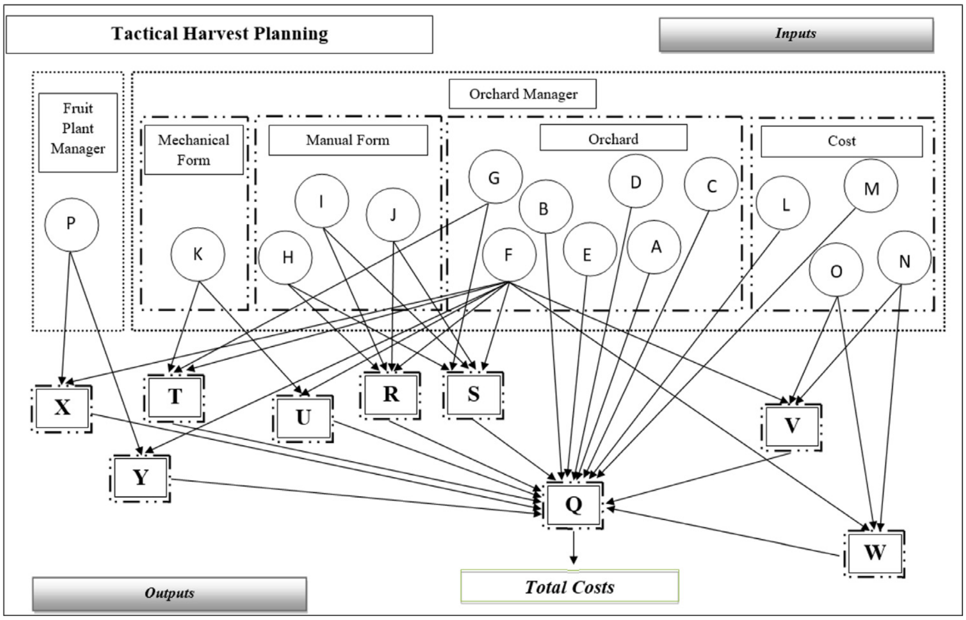


Fig. 1. Relationship scheme of inputs and outputs for planning a fruit harvest season for multiple orchards.

real case study in order to compare the obtained results. Section 6 presents managerial insights about the main results obtained. Finally, the main conclusions of this study and future research to pursue are presented in Section 7.

2. Fruit harvest planning

During a harvest season, fruit must be picked in a relatively short and intense period in order to supply fresh fruit to agri-industrial companies. For this reason, farmers or orchard managers must estimate in advance the required quantities of labor, raw materials, machinery, and transport according to a forecasted harvest calendar for each planted fruit variety. An anticipated harvest plan is necessary so that the required resources are available at the beginning of the harvest since purchases and contracts must be done at least two months in advance. Currently, orchard managers take up to three weeks to prepare a fruit harvest plan and it is difficult for them to analyze different scenarios if some harvest conditions vary. Furthermore, the fruit harvest plan becomes more complex when multiple orchards are managed during a season, which is a common situation for large fruit export companies.

In every orchard, the fruit tree plantations are usually divided in blocks (specific areas of land with similar characteristics in ground composition, fruit species, variety, age, density, and quality). Moreover, some fruit species require the cross-pollination of two or more varieties. In these cases, two different varieties are frequently planted in a block: a predominant variety and a pollinating variety. The pollinating variety is necessary for setting the fruit production of the predominant variety. This situation makes the planning process more complex because the predominant and pollinating varieties usually do not ripen at the same time and both must be harvested. Consequently, these harvests are done in different time periods.

It is important to mention that for some fruit species or varieties the fruits mature at the same time; therefore, they need to be picked only once during a season. This type of harvest is known as strip picking. However, other fruit species or varieties do not ripen at the same time and thus, they must be collected more than once during a season. This type of harvest is known as selective picking and the number of harvests per season depends on the fruit species or variety (see González-Araya et al. 2015).

Regarding the forms to collect fruit, usually there are workers (manual form) and/or machinery (mechanical form). The selection of these harvesting methods depends on the fruit species or variety, distance from the consumer markets, shape of the blocks, and available technology in the orchards. For example, the harvest machinery frequently damages the fruit slightly. Therefore, if the consumer market is too far from the orchards, this form of harvesting is not recommended because some bruises on the fruit could appear during the trip and, consequently, the fruit sale price could diminish.

During a harvest season, orchard managers can hire permanent or temporary workers. Permanent workers are hired during the whole harvest season, while temporary workers are hired for short time periods. In some periods of the harvest season, it is possible to observe that permanent workers are idle. This situation occurs mainly when the harvest season is not at its peak.

As mentioned previously, most fruit export companies have several orchards, increasing the complexity of planning decisions. In this sense, it is not only necessary to know how many kinds of workers are required to harvest the fruit, but also which orchard and block they should be assigned and what type of harvest should be done (selective picking or strip picking). It is important to highlight that machinery is usually not shared among different orchards; however, it is possible to assign it to more than one block during a day.

Sometimes, there are blocks in the orchards that have a similar harvest period. When this occurs, it is desirable that their harvest is carried out continuously and not in different intervals so that it is easier to identify when the harvest has been completed. For this reason, the harvest of each block must be performed in consecutive days. In addition, if blocks need to be harvested by selective picking, the first selective picking must start before the second selective picking and must finish before the end of the second selective picking. This precedence is similar between the second and third selective picking and so on. It is important to note that the maximum number of selective pickings during a harvest season depends on the fruit species and its variety.

Table 1
Input and output information required for planning the fruit harvest of multiple orchards.

Source	Input Information	Output Report
Orchard Manager	A. Harvest planning horizon B. Number of orchards C. Number of blocks in each orchard D. Kind of fruit varieties planted in each block (predominant and pollinating) E. Harvest window for each variety in each block F. Estimated fruit quantity and quality during the harvest planning horizon for each variety in each block G. Form of harvesting required in each block (manual or mechanical) If a block requires a manual form of harvesting: H. Type of workers (permanent or temporary) I. Maximum number of available workers of each type J. Productivity rate of each type of worker If a block requires a mechanical form of harvesting: K. Productivity rate of the mechanical form of harvesting L. Costs of manual harvest M. Costs of mechanical harvest N. Estimated cost of fruit loss O. Bin capacity according to each fruit variety	Q. Tactical harvest plan for orchards R. Hiring and dismissing plan of workers S. Worker assignment to each block T. Use plan of machine hours U. Assignment of machine hours to each block V. Bins' requirement plan W. Bins' assignment to each block
Fruit Plant Manager	P. Daily plant capacity for each purpose (export or national market)	X. Fruit receiving plan Y. Daily fruit received in each plant according to each variety and purpose

Another important issue to be considered during a harvest season corresponds to the daily capacities of the plants for processing fresh fruit. Every plant capacity is estimated according to the minimum capacity among the fruit reception, storage, and processing, that is, according to the bottleneck capacity of the plant. Maximum plant capacity also depends on the fruit species or variety to be processed. Therefore, every processing plant establishes the daily fruit quantities that can be received from each farmer in order to not surpass the plant capacity. This means that every orchard must not harvest more fruit than the processing plant can receive.

According to the information and restrictions described previously, it is necessary to incorporate them in an integrated manner to plan the entire harvest season and avoid discoordination in the posterior stages of the FSC. Table 1 presents the input and output information required by orchard and fruit plant managers for organizing the harvest season of multiple fruit orchards. In addition, Fig. 1 illustrates the relationship between the input information and the output report in order to understand the importance of every input and the complexity of the harvest planning process.

As illustrated in Fig. 1, a lot of interrelated information is required simultaneously for planning a fruit harvest season for multiple orchards. It is possible to observe in Table 1 and Fig. 1 that the tactical harvest planning has two areas: orchard manager and fruit plant manager. The orchard manager area corresponds to the information and decisions carried out inside an orchard, while the fruit plant manager area corresponds to the information and decisions made inside a fruit processing plant. In the orchard manager area, there are four types of information: orchard characteristics, mechanical harvest, manual harvest, and costs. All this input information must be collected and analyzed to prepare the harvest plan in an orchard (Output Report Q in Table 1). Once the partial output reports are obtained (R, S, T, U, V, W, X and Y), it is possible to produce the tactical harvest plan. These reports are presented in Table 1 and illustrated in Fig. 1. For example, as observed in Fig. 1, for obtaining the "Bins' requirement plan" (Output Report V), it is required to develop the reports F, N, and O. In addition, once the output report Q is obtained, the total costs of the harvest plan can be calculated.

3. Optimization model for the tactical harvest planning of multiple orchards

The tactical planning harvest model developed in this study incorporates all the aspects described in Section 2 and is formulated as a MILP model.

Table 2 presents the sets and parameters used in the mathematical model, while Table 3 describes the decision variables of the model.

The objective function can be broken down into nine terms in order to facilitate the readers' comprehension.

$$Z_1 = \sum_{t \in T} \sum_{\substack{\langle o,c,f \rangle \in A \\ c \in C_{o1}}} HMQ_{cft} Q \tag{1}$$

$$Z_2 = (H_r + F_r) THF \tag{2}$$

$$Z_3 = \sum_{t \in T} H_v THV_t. \tag{3}$$

$$Z_4 = \sum_{t \in T} F_v TFV_t \tag{4}$$

$$Z_5 = \sum_{t \in T} \sum_{\substack{\langle o,c,f \rangle \in A \\ c \in C_{o2}}} J_{ocfr} TFC_{ocft} \tag{5}$$

$$Z_6 = \sum_{t \in T} \sum_{\substack{\langle o,c,f \rangle \in A \\ c \in C_{o2}}} J_{ocfv} TVC_{ocft}. \tag{6}$$

$$Z_7 = Po \sum_{t \in T} BF_t \tag{7}$$

Table 2
Definition of sets and parameters used in the tactical harvest planning model.

Sets and Parameters	
K	Form of harvesting, $K=\{1$: mechanical harvest, 2: manual harvest$\}$.
EO	Number of orchards.
O	Set of orchards, $O=1, 2, \ldots, EO$.
C_{ok}	Set of blocks belonging to an orchard o that use the harvest option k, where $o \in O$, $k \in K$.
C_o	Set of blocks to be harvested in the orchard o, where $o \in O$, $C=C_{o1} \cup C_{o2}$ y $C_{o1} \cap C_{o2}=\emptyset$.
U	Set of worker types, where $U=\{r$: permanent worker, v: temporary worker$\}$.
P	Set of processing plants to send the harvested fruit, $P=\{e$: export, n: national market$\}$.
PH	Number of days of the harvest planning horizon.
T	Set of days for harvesting the orchards, $T=1, 2, \ldots, PH$.
PA_{oc}	Number of harvest types to be carried out in a block c, belonging to an orchard o, where $o \in O$, $c \in C_o$.
F_{oc}	Sets of harvest types by which a block c must be harvested in an orchard o, F_{oc}=1,2,…,PA_{uo}, where o ∈ O, $c \in C_o$.
$\mathcal{A}$	Set of tuples $\langle o,c,f \rangle$ that identifies that a block c, belonging to an orchard o, that is harvested according to the type of harvest f, where $o \in O, c \in C_o,\ f \in F_{oc}$.
A_{ocft}	Percentage of fruit loss due to poor quality in a block c, belonging to an orchard o, using the type of harvest f, in the period t, where $\langle o,c,f \rangle \in \mathcal{A}$, $t \in T$.
H_{u}	Unit cost of hiring a worker type u, where $u \in U$.
F_{u}	Unit cost of dismissing a worker type u, where $u \in U$.
J_{ocfu}	Salary of a worker type u, in each period, in the block c, belonging to the orchard o, where $o \in O$, $c \in C_{o2}$, $\langle o,c,f \rangle \in \mathcal{A}$.
Q	Cost per hour for using a machine in the harvest.
Pi_{ocf}	Productivity of the mechanical harvest in the block c, belonging to an orchard o, with the type of harvest f, expressed in kilograms/hour, where c $\in C_{o1}$, $\langle o,c,f \rangle \in \mathcal{A}$.
Ri_{ocf}	Productivity of the manual harvest done by a permanent worker in the block c, belonging to an orchard o, with the type of harvest f, expressed in kilograms/worker, where $c \in C_{o2}$, $\langle o,c,f \rangle \in \mathcal{A}$.
Si_{ocf}	Productivity of the manual harvest done by a temporary worker in the block c, belonging to an orchard o, with the type of harvest f, expressed in kilograms/worker, where $c \in C_{o2}$, $\langle o,c,f \rangle \in \mathcal{A}$.
D_{ocf}	Kilograms of fruit to be harvested in a block c, belonging to an orchard o, through the type of harvest f, where $\langle o,c,f \rangle \in \mathcal{A}$.
G_{pt}	Maximum kilograms of fruit that can be processed in the plant p, during the period t, where $p \in P$, t $\in T$.
N_{ocft}	Maximum kilograms of fruit that can be harvested in a block c, belonging to an orchard o, through the type of harvest f, in the period t, where $\langle o,c,f \rangle \in \mathcal{A}$, $t \in T$.
L_k	Minimum kilograms of fruit that can be harvested in one period, for each block, using harvest form k, where $k \in K$.
I_{ot}	Maximum number of available machinery hours in an orchard o, during the period t, where $o \in O$, $t \in T$.
λ	Penalty parameter for harvesting fruit without the required maturity conditions, measured in monetary units/kilograms of fruit wasted.
Ni	Minimum number of permanent workers required for the harvest.
W	Maximum number of temporary workers for the harvest, which is the same in every period.
E	Maximum kilograms that a bin can contain (container to load the fruit).
PL_{ocfp}	$PL_{ocfp} \in \{0, 1\}$, where $PL_{ocfp=}$ 1 indicates that the fruit of block c, belonging to the orchard o, with the type of harvest f, is sent to the plant p, $PL_{ocfp=}$ 0 otherwise, where $\langle o,c,f \rangle \in \mathcal{A}$, $p \in P$.
Po	Cost of having an idle worker in a period.
β	Penalty parameter per every additional harvest day, which is measured in monetary units/harvest day.
M_1	Very large positive scalar measured in harvest kilograms.
M_2	Very large positive scalar used for the maximum days of the planning horizon.

Table 3
Decision variables of the tactical harvest planning model.

Decision variables	
X_{ocft}	Kilograms of fruit to be harvested in the block c, belonging to an orchard o, through the type of harvest f, in the period t, where $\langle o,c,f \rangle \in \mathcal{A}$, $t \in T$.
Y_{ocft}	$Y_{ocft} \in \{0, 1\}$, where $Y_{ocft}=1$, if the block c, belonging to the orchard o, through the type of harvest f, in the period t, is harvested; $Y_{ocft}=0$ otherwise, where $\langle o,c,f \rangle \in \mathcal{A}$, $t \in T$.
THF	Number of permanent workers to hire during the harvest season.
THV_t	Number of temporary workers to hire at the beginning of the period t, where $t \in T$.
TFV_t	Number of temporary workers to fire at the end of the period t, where $t \in T$.
TFC_{ocft}	Number of permanent workers to be assigned to a block c, belonging to an orchard o, according to the type of harvest f, in period t, where $c \in C_{o2}$, $\langle o,c,f \rangle \in \mathcal{A}$., $t \in T$.
TVC_{ocft}	Number of temporary workers to be assigned to a block c, belonging to an orchard o, according to the type of harvest f, in the period t, where $c \in C_{o2}$, $\langle o,c,f \rangle \in \mathcal{A}$, $t \in T$.
HMQ_{ocft}	Hours of machinery necessary for harvesting a block c, belonging to an orchard o, according to the type of harvest f, in the period t, where $c \in C_{o1}$, $\langle o,c,f \rangle \in \mathcal{A}$, $t \in T$.
NB_{ocft}	Number of bins needed in the block c, belonging to an orchard o, according to the type of harvest f, in the period t, where $\langle o,c,f \rangle \in \mathcal{A}$, $t \in T$.
SL_{ocf}	Kilograms of fruit not harvested in the block c, belonging to an orchard o, through the type of harvest f, in the period t, where $\langle o,c,f \rangle \in \mathcal{A}$, $t \in T$.
BF_t	Number of idle permanent workers in the period t, where $t \in T$.
TV_t	Number of tempora workers during the period t, where $t \in T$.
INI_{ocft}	Kilograms of available fruit in the block c, belonging to the orchard o, according to the type of harvest f, at the end of the period t, where $\langle o,c,f \rangle \in \mathcal{A}$, $t \in T$.
WI_{ocft}	$WI_{ocft} \in \{0,1\}$, where $WI_{ocft}=1$ if the block c, belonging to the orchard o, according to the type of harvest f, at the end of period t, has the minimum fruit kilograms to be harvested; $WI_{ocft}=0$ otherwise, where $\langle o,c,f \rangle \in \mathcal{A}$, $t \in T$.
FI_{ocf}	Period when the block c, belonging to the orchard o, begins to be harvested through the type of harvest f, where $\langle o,c,f \rangle \in \mathcal{A}$.
FT_{ocf}	Period when the block c, belonging to the orchard o, finishes to be harvested through the type of harvest f, where $\langle o,c,f \rangle \in \mathcal{A}$.

$$Z_8 = \sum_{\langle o,c,f\rangle\in\mathcal{A}} \sum_{t\in T} A_{ocft} X_{ocft} \tag{8}$$

$$Z_9 = \sum_{\langle o,c,f\rangle\in\mathcal{A}} SL_{ocf} \tag{9}$$

$$Z_{10} = \sum_{t\in T} \sum_{\langle o,c,f\rangle\in\mathcal{A}} t \times Y_{ocft} \tag{10}$$

Eq. (1) represents the costs of mechanical harvesting. Eq. (2) represents the costs of hiring and dismissing permanent workers. Eq. (3) and Eq. (4) represent the costs of hiring and dismissing temporary workers, respectively. Eq. (5) and Eq. (6) represent the salaries of permanent and temporary workers, respectively. Eq. (7) represents the costs of keeping idle permanent workers. Eq. (8) corresponds to the fruit harvested without the required maturity condition. Eq. (9) represents the unharvested fruit. Eq. (10) seeks to compact the harvesting calendar.

The objective function aims to minimize all the costs associated with the terms described previously. Thus, the mathematical formulation of the tactical model is the following:

$$\min Z = Z_1 + Z_2 + Z_3 + Z_4 + Z_5 + Z_6 + Z_7 + \lambda(Z_8 + Z_9) + \beta Z_{10} \tag{11}$$

s.t.

$$\sum_{\langle o,c,f\rangle\in\mathcal{A}} PL_{ocfp} X_{oct} \le G_{pt}, \qquad p\in P,\ t\in T \tag{12}$$

$$\sum_{t\in T} X_{ocft} + SL_{ocf} = D_{ocf}, \ \langle o,c,f\rangle\in\mathcal{A} \tag{13}$$

$$SL_{ocf} \le L_k, \quad k\in K,\ c\in C_{ok},\ \langle o,c,f\rangle\in\mathcal{A} \tag{14}$$

$$X_{ocft} \le N_{ocft} Y_{ocft}, \quad \langle o,c,f\rangle\in\mathcal{A}, t\in T \tag{15}$$

$$X_{ocft} \ge L_k Y_{ocft}, \quad k\in K,\ c\in C_{ok}\ ,\ \langle o,c,f\rangle\in\mathcal{A},\ t\in T \tag{16}$$

$$X_{ocft} \le \ Pi_{ocf} HMQ_{ocft}, \quad c\in C_{o1},\ \langle o,c,f\rangle\in\mathcal{A},\ t\in T \tag{17}$$

$$X_{ocft} \le Ri_{ocf} TFC_{ocft} + Si_{ocf} TVC_{ocft}, \quad c\in C_{o2},\ \langle o,c,f\rangle\in\mathcal{A},\ t\in T \tag{18}$$

$$NB_{ocft} E \ge X_{ocft}, \quad \langle o,c,f\rangle\in\mathcal{A}, t\in T \tag{19}$$

$$\sum_{\substack{\langle o,c,f\rangle\in\mathcal{A}\\ c\in\ C_{o1}}} HMQ_{ocft} \le I_{ot}, \quad t\in T,\ o\in O \tag{20}$$

$$\sum_{\substack{\langle o,c,f\rangle\in A\\ c\in C_{o2}}} TFC_{ocft} + BF_t = THF, \quad t\in T \tag{21}$$

$$THF \ge Ni \tag{22}$$

$$\sum_{\substack{\langle o,c,f\rangle\in A\\ c\in C_{o2}}} TVC_{ocft} \le W, \quad t\in T \tag{23}$$

$$\sum_{\substack{\langle o,c,f\rangle\in A\\ c\in C_{o2}}} TVC_{ocft} = TV_t, \quad t\in T \tag{24}$$

$$\sum_{\substack{\langle o,c,f\rangle\in A\\ c\in C_{o2}}} TVC_{ocf1} = THV_1 \tag{25}$$

$$TV_t = TV_{t-1} + THV_t - TFV_{t-1}, \quad t\in T : t\ge 2 \tag{26}$$

$$\sum_{\substack{\langle o,c,f\rangle\in A\\ c\in C_{o2}}} TVC_{ocfPH} = TFV_{PH} \tag{27}$$

$$INI_{ocft}\ -\ L_k\ \le\ M_1 WI_{ocft},\ k\in K,\ c\in C_{ok},\ \langle o,c,f\rangle\in\mathcal{A},\ t\in T \tag{28}$$

$$INI_{ocft}\ -\ L_k\ \ge\ M_1(WI_{ocft}-1),\ \ k\in K,\ c\in C_{ok},\ \langle o,c,f\rangle\in\mathcal{A},\ t\in T \tag{29}$$

$$INI_{ocf1} = D_{ocf} - X_{ocf1}, \quad \langle o,c,f\rangle\in\mathcal{A} \tag{30}$$

$$INI_{ocft} = INI_{ocft-1} -\ X_{ocft}, \quad \langle o,c,f\rangle\in\mathcal{A},\ t\in T; \tag{31}$$

$$Y_{ocft}\ +\ WI_{ocft}\ \le\ Y_{ocft+1} +\ 1, \quad \langle o,c,f\rangle\in\mathcal{A},\ t\in T \tag{32}$$

$$t - FI_{ocf} \ge M_2\big(Y_{ocft+1} - 1\big), \quad \langle o,c,f\rangle\in\mathcal{A},\ t\in T \tag{33}$$

$$FT_{ocf} - t \ge M_2\big(Y_{ocft+1} - 1\big), \quad \langle o,c,f\rangle\in\mathcal{A},\ t\in T \tag{34}$$

$$FT_{ocf} = FI_{ocf}\ +\ \sum_{t\in T} Y_{ocft} - 1, \quad \langle o,c,f\rangle\in\mathcal{A} \tag{35}$$

$$FI_{ocf} + 1 \le FI_{ocf+1}, \quad \langle o,c,f\rangle\in\mathcal{A} \tag{36}$$

$$FT_{ocf} + 1 \le FT_{ocf+1}, \quad \langle o,c,f\rangle\in\mathcal{A} \tag{37}$$

$$Y_{ocft},\ WI_{ocft}\ \in\{0,1\}, \quad \langle o,c,f\rangle\in\mathcal{A}, t\in T \tag{38}$$

$$X_{ocft},\ HMQ_{ocft},\ S_{ocf},\ INI_{ocft} \ge 0, \quad \langle o,c,f\rangle\in\mathcal{A}, t\in T \tag{39}$$

$$THF,\ NB_{ocft},\ TFC_{ocft},\ TVC_{oft},\ FI_{ocf},\ FT_{ocf}\in Z^+,\ \ \langle o,c,f\rangle\in\mathcal{A}, t\in T \tag{40}$$

$$THV_t,\ TFV_t, BF_t,\ TV_t\in Z^+, \quad t\in T \tag{41}$$

The objective function (11) seeks to minimize three different items. The first item (objective 1) is to minimize harvesting costs, being these the sum of Z_1, Z_2, Z_3, Z_4, Z_5, Z_6. Z_7. The second item (objective 2) corresponds to the costs of wasted fruit, which is represented by the sum $Z_8.+Z_9$ multiplied by λ (USD$/kilograms). Finally, the third item (objective 3) involves the cost of extending the harvesting calendar and is estimated by multiplying β (USD$/harvesting day) by Z_{10}. In this sense, these three items are considered in a mono-objective function. The parameters λ and β are estimated according to weights (Haghani, 1996), aiming for the optimal mono-objective function to be located at an extreme point of the multi-objective efficient frontier.

Constraints (12) to (18) establish the minimum and maximum fruit quantities that can be harvested during a day. Constraint (12) ensures that the harvested fruit does not exceed the plants' capacities. Constraint (13) ensures that all the fruit in a block must be equal to the harvested and unharvested fruit in the block. Constraint (14) guarantees that the unharvested fruit in a block is less than the minimum quantity. Constraint (15) ensures that the fruit in a block can be harvested only if the decision for harvesting was previously made for that block. Constraint (16) indicates that if it is decided to harvest a block, the fruit harvested must exceed the minimum amount. Finally, constraints (17) and (18) establish that the fruit harvested in a block does not exceed the daily productivity of mechanical and manual harvest, respectively. Constraints (19) to (27) consider all the necessary resources for harvesting daily. Constraint (19) allows estimating the daily number of bins for each block in order to pick up all the harvested fruit. Constraint (20) establishes that the daily machine hours must be less than the available machine hours. Constraint (21) ensures that the daily number of permanent workers assigned to a block and that the number of idle workers is equal to the number of hired permanent workers. Constraint (22) guarantees that the number of hired permanent workers is greater than or equal to a defined minimum number. Constraint (23) establishes that it is not possible to assign more temporary workers daily in all the blocks than a defined maximum number. Constraint (24) ensures that the daily number of hired temporary workers is equal to the daily number of temporary workers assigned to the blocks. Constraints (25) to (27) allow balancing the number of hired and dismissed temporary workers in order to assign them to the blocks. Constraints (28) to (32) ensure the harvest in a block is done in consecutive days. Constraints (28) and (29) establish if a block can be harvested in the following day according to the minimum quantity of available fruit. Constraints (30) and (31) allow estimating the daily amount of available fruit in the blocks. Constraint (32) establishes if a block will be harvested the next day by considering if the block had been harvested on the current day and if there remains enough fruit to be harvested on the following day. Constraints (33) to (37) estimate the harvest window for a block and ensure that the precedence of the different types of harvest is respected. For example, the first selective picking in a block must start at least one day before the beginning of the second selective picking in that block and must finish at least one day before than the end of the second selective picking. Constraints (33) and (34) establish that it is not possible to harvest fruit in a block before and after the estimated harvest window. Constraint (35) guarantees, for a block, that the end of the estimated harvest window is equal to its beginning plus the number of harvesting days. Finally, constraints (36) and (37) ensure that the precedence of the different types of harvest is respected. Constraints (38) to (41) correspond to restrictions about the nature of the decision variables.

When this MILP model was applied to a real case (Section 5), the exact method took such a long time to find an optimal solution that we developed an algorithmic solution method to approximate the optimal solution.

4. GRASP metaheuristic developed for tactical harvest planning

For solving the proposed MILP model, an algorithm based on the GRASP was developed. The GRASP metaheuristic has two phases: a constructive phase, where an initial solution is built, and a local search phase, where the solution is improved (Resende & Ribeiro, 2014). As mentioned previously, some metaheuristic algorithms used for solving optimization models in agri-food supply chain were presented by Musavi et al. (2017), Mogale et al. (2017) and Cheraghalipour et al. (2019). These authors analyzed different metaheuristic approaches than this study. In this regard, we selected the GRASP metaheuristic for solving the tactical planning harvest model because of the constructive phase, which seeks feasible solutions based on an optimization criterion. This phase has the advantage of obtaining good initial solutions, reducing the execution time of the local search phase and, consequently, the execution time of the GRASP metaheuristic.

A description of each phase of the GRASP metaheuristic is presented in the following sub-sections and details of the GRASP metaheuristic are presented in Appendix A.1.

4.1. Constructive phase: randomized constructive method

For implementing a randomized constructive method, development of the following functions is required: solution generating function, cost function, and selection function. Before describing these functions, it is important to mention that permanent workers are not specified a priori when constructing the solution, that is, $THF = 0$. At the end of the algorithm, the number of permanent workers to be hired is calculated. This is possible because it is assumed that permanent and temporary workers have the same productivity. On the other hand, because a solution could exceed the maximum processing plant capacity and/or the number of available machine hours, the set of solutions could be empty. If this situation occurs, the constructive method is restarted.

The constructive method begins by randomly selecting a block. When a block is selected, the types of harvest are determined according to the order that they are done during the harvest, for example, first selective picking, second selective picking, and strip picking. Once a block with a type of harvest is selected, the respective harvest window is reviewed, assigning harvest resources to each day of the window. On each day, the selection function indicates if workers or machine hours can be assigned on that day, according to the harvest form of the block (manual or mechanical). If the harvest form is manual, a worker will be assigned as long as the plant capacity constraint allows it. If the harvest form is mechanical, the maximum number of machine hours will be assigned if the available number of machine hours is different from zero. In this case, the plant capacity constraint must also be abided. Once an assignment for a given day has been made, the respective incremental cost is calculated. Furthermore, each time an assignment is made, it is verified if the minimum fruit quantity allows the block to be harvested. If not, fruit is left in the block. This means that the selection function can choose whether to allocate the resources (workers or machine hours) to the block or leave fruit unharvested. Next, the decision variable values are updated and the constructive method iterates again. This method is repeated until the total harvested and unharvested fruit is equal to the fruit available for the harvest at the beginning of the constructive phase. Finally, once all the blocks have received the necessary resources (workers or machine hours), the total costs are calculated.

4.1.1. Solution generating function

There are different conditions that allow establishing the feasibility of solutions, such as:

- Type of harvest in a block. According to the type of harvest to carry out in a block, such as first selective picking, second selective picking, or strip picking, the days for harvesting will vary. In this way, if a type of harvest has already been done in a block, the first worker of the following type of harvest must not be assigned until a day before the end of the previous type of harvest. This is done for ensuring that the next type of harvest finishes at least one day after the previous one. Therefore, new workers can only be assigned one day after the start of the previous type of harvest. The harvest window of each type of harvest will depend on the fruit ripeness curve, which is represented by the parameter A of the mathematical model.
- Previous workers' assignments. It is relevant to determine if workers have been previously assigned to a block for a certain type of harvest because it is necessary to assure harvest continuity. If no workers have been assigned to a block for one type of harvest, a worker can be assigned to any day of the harvest

window. Otherwise, the workers can be assigned only on the days that have already had workers or on adjacent days.
- Available fruit in a block. It is important to estimate if there is enough fruit to harvest in a block because there is a minimum quantity of fruit needed to cover the harvest costs. In case there is less fruit than the minimum quantity established, new workers can only be assigned to a block on the days where workers had already been assigned to harvest the remaining fruit. Otherwise, it is possible to leave the remaining fruit in the block.

4.1.2. Costs function

The partial cost function allows calculating the cost associated with a single block according to a type of harvest. Therefore, the costs added to this function correspond to Z_1, Z_3, Z_4, Z_6, Z_8, and Z_9 established in Eqs. (1), (3), (4), (6), (8), and (9), respectively. The value obtained in the partial cost function is used in the selection function, as detailed below.

There is also the function of total cost, which calculates all the costs obtained at the end of the construction phase. In this way, all costs established in the objective function (11) are summed and the value of the total cost is used in the local search.

4.1.3. Selection function

This function selects one of the days obtained with the solution generating function. For this purpose, it is assigned to the parameters S_{min} and S_{max}, the lowest and highest partial cost, respectively, obtained by the partial cost function. Then, the set *RCL* is built, which must contain all the days in which the partial cost is in the interval $[S_{min}, S_{min} + \alpha\ (S_{max} - S_{min})]$. The parameter α is a scalar that can take any value between 0 and 1. If the value of α is equal to 0, there is no randomness in the selection criteria and *RCL* will be compounded by the day or days that have a partial cost function equal to S_{min}. On the other hand, if α is equal to 1, *RCL* will be formed by all the days obtained by the solution generating function because all of them will have a partial cost function between S_{min} and S_{max}.

Once the set *RCL* is obtained, one of the days belonging to this set is chosen randomly. According to this selection, the start and end days of the harvest should be updated if necessary.

Fig. 2 illustrates how the three functions described above interact to obtain a good quality initial solution considering manual and mechanical harvest.

The next sub-section describes the local search phase of the GRASP, which aims to improve the solution obtained by the construction method.

4.2. Local search phase

In the local search phase, three neighborhood functions are developed aiming to reduce the costs associated with fruit quality (Z_8), the extension of the harvest calendar (Z_{10}), and the use of labor (Z_2, Z_3, Z_4 and Z_7). For improving labor costs, the wage cost is not considered because it is calculated according to the harvested fruit quantity; therefore, it is not desirable to reduce it. The GRASP metaheuristic uses any of these three neighborhood functions for reducing costs, choosing each in a random way. In the following sub-sections, a description of each neighborhood function is presented.

4.2.1. Neighborhood function 1: harvest window displacement of a block

This function starts with the random choice of a block. Then, from the chosen block, a type of harvest is arbitrarily selected. Once this is done, the function evaluates if it is possible to move its harvest window either one day before the beginning or one day after the end of the window. Hence, it is evaluated if the precedence constraint between the types of harvest is maintained. In the case that it is feasible to do either of the two movements, one of them is randomly selected. Otherwise, the feasible movement is chosen or none of them are chosen in case of infeasibility. If the total cost function of the new solution is less than or equal to the current solution, the solution is replaced by the new one. An example of this neighborhood function is presented in Appendix A.3.1.

4.2.2. Neighborhood function 2: shift of workers or machine hours in a block

In this function, a block and one of its types of harvest are chosen randomly if the harvest window lasts more than one day. From the selected harvest window, two days are chosen arbitrarily. If the block is harvested manually, a worker from one of the selected days is moved to the other selected day if there is more than one worker on the given day in order to keep the harvest continuity. If the block is harvested mechanically, the total machine hours assigned to each day are shifted. Then, the total cost of the new solution is calculated. If it is less than or equal to the current solution, the current solution is replaced by the new one. An example of this neighborhood function is presented in Appendix A.3.2.

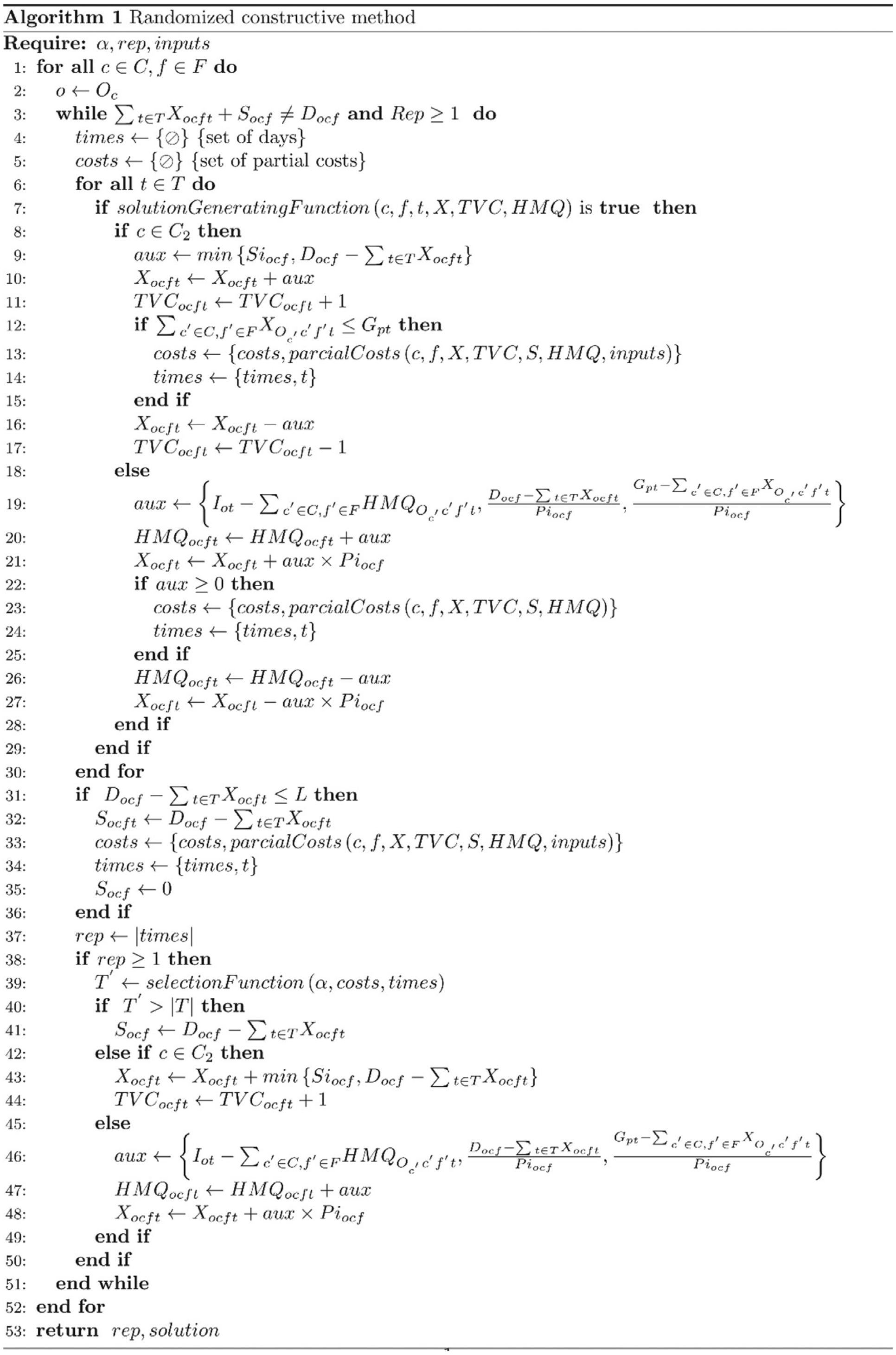
4.2.3. Neighborhood function 3: shift of workers or machine hours between two blocks

This function begins by randomly choosing two types of harvest that can belong to the same block or to different blocks. If the harvest windows overlap each other and have the same harvest mode, the first and last days of this overlap are identified. In the case that they do not overlap and/or do not have the same harvest mode, the local search method ends. Once this overlap has been identified, it is necessary to determine which day possesses the lowest quantity of kilograms to be harvested. If the day with the lowest quantity of kilograms is at the end of the window, all kilograms and the respective workers or machine hours must be assigned to the same day of the other type of harvest. In the case that the lowest quantity of kilograms is not at one of the ends of the window, the change is not carried out since the continuity of the harvest would be lost.

The type of harvest that receives the kilograms and the workers or machine hours must re-assign the same quantity that it receives to the other type of harvest. This re-assignment must be done in the opposite extreme day of the overlap. In this way, the total kilograms harvested in each block for every type of harvest and the total kilograms harvested per day are kept constant. After this procedure, the function of total costs is calculated. If these are less than or equal to the current solution, this new solution is chosen as the current solution. An example of this neighborhood function is presented in Appendix A.3.3.

4.3. Computational experimentation

A computational experiment was carried out using 92 fictitious instances that have diverse orchard sizes and harvesting forms (manual or mechanical). In this experiment, the exact solution method CPLEX 12.5 was used in order to determine the size of the mathematical problem, but its computational time became too prohibitive to continue searching. In addition, these instances are used for adjusting the metaheuristic parameters and determining the stop criterion. In the experiment, it was observed that CPLEX always obtained the exact optimal solution for instances that considered mechanical harvesting. For these same instances, the GRASP metaheuristic obtained the same solution as CPLEX most of the time; in the worst case scenario, it had a few differences with the CPLEX objective function. On the other hand, for instances that considered manual harvesting, this experimentation showed that the metaheuristic obtained an objective function



```
Algorithm 1 Randomized constructive method
Require: $\alpha, rep, inputs$
for all $c \in C, f \in F$ do
  $o \leftarrow O_c$
  while $\sum_{t \in T} X_{ocft} + S_{ocf} \neq D_{ocf}$ and $Rep \geq 1$ do
    $times \leftarrow \{\emptyset\}$ {set of days}
    $costs \leftarrow \{\emptyset\}$ {set of partial costs}
    for all $t \in T$ do
      if $solutionGeneratingFunction(c, f, t, X, TVC, HMQ)$ is true then
        if $c \in C_2$ then
          $aux \leftarrow min\{Si_{ocf}, D_{ocf} - \sum_{t \in T} X_{ocft}\}$
          $X_{ocft} \leftarrow X_{ocft} + aux$
          $TVC_{ocft} \leftarrow TVC_{ocft} + 1$
          if $\sum_{c' \in C, f' \in F} X_{O_{c'}c'f't} \leq G_{pt}$ then
            $costs \leftarrow \{costs, parcialCosts(c, f, X, TVC, S, HMQ, inputs)\}$
            $times \leftarrow \{times, t\}$
          end if
          $X_{ocft} \leftarrow X_{ocft} - aux$
          $TVC_{ocft} \leftarrow TVC_{ocft} - 1$
        else
          $aux \leftarrow \left\{ I_{ot} - \sum_{c' \in C, f' \in F} HMQ_{O_{c'}c'f't}, \frac{D_{ocf} - \sum_{t \in T} X_{ocft}}{Pi_{ocf}}, \frac{G_{pt} - \sum_{c' \in C, f' \in F} X_{O_{c'}c'f't}}{Pi_{ocf}} \right\}$
          $HMQ_{ocft} \leftarrow HMQ_{ocft} + aux$
          $X_{ocft} \leftarrow X_{ocft} + aux \times Pi_{ocf}$
          if $aux \geq 0$ then
            $costs \leftarrow \{costs, parcialCosts(c, f, X, TVC, S, HMQ)\}$
            $times \leftarrow \{times, t\}$
          end if
          $HMQ_{ocft} \leftarrow HMQ_{ocft} - aux$
          $X_{ocft} \leftarrow X_{ocft} - aux \times Pi_{ocf}$
        end if
      end if
    end for
    if $D_{ocf} - \sum_{t \in T} X_{ocft} \leq L$ then
      $S_{ocft} \leftarrow D_{ocf} - \sum_{t \in T} X_{ocft}$
      $costs \leftarrow \{costs, parcialCosts(c, f, X, TVC, S, HMQ, inputs)\}$
      $times \leftarrow \{times, t\}$
      $S_{ocf} \leftarrow 0$
    end if
    $rep \leftarrow |times|$
    if $rep \geq 1$ then
      $T' \leftarrow selectionFunction(\alpha, costs, times)$
      if $T' > |T|$ then
        $S_{ocf} \leftarrow D_{ocf} - \sum_{t \in T} X_{ocft}$
      else if $c \in C_2$ then
        $X_{ocft} \leftarrow X_{ocft} + min\{Si_{ocf}, D_{ocf} - \sum_{t \in T} X_{ocft}\}$
        $TVC_{ocft} \leftarrow TVC_{ocft} + 1$
      else
        $aux \leftarrow \left\{ I_{ot} - \sum_{c' \in C, f' \in F} HMQ_{O_{c'}c'f't}, \frac{D_{ocf} - \sum_{t \in T} X_{ocft}}{Pi_{ocf}}, \frac{G_{pt} - \sum_{c' \in C, f' \in F} X_{O_{c'}c'f't}}{Pi_{ocf}} \right\}$
        $HMQ_{ocft} \leftarrow HMQ_{ocft} + aux$
        $X_{ocft} \leftarrow X_{ocft} + aux \times Pi_{ocf}$
      end if
    end if
  end while
end for
return $rep, solution$
```

Fig. 2. Pseudocode of the constructive method.

value about 2% higher than the lowest limit obtained by CPLEX. For these instances, CPLEX did not yield an exact solution after 7200 s. In addition, the computational time required by the metaheuristic to find a good solution was much lower than that required by CPLEX. For example, the instance that required the highest computational time with the metaheuristic was seven times less than that required by CPLEX. This illustrates the good quality and efficiency of the developed GRASP metaheuristic.

In the following section, we present the results for a real case study that shows the usefulness and viability of the solution obtained by the GRASP metaheuristic for the orchard managers. In addition, the performance of the GRASP metaheuristic and the exact method (CPLEX 12.5) are compared.

5. Case study

The case study is based on a real situation of a Chilean agriindustrial company that has six orchards with four apple varieties (Granny Smith, Fuji, Gala, and Red). The fresh fruit production of these orchards is destined for export, mainly for countries in Europe, Asia, and the Northern Hemisphere. The data were obtained from the 2014–2015 harvest season. It is important to mention that

Table 4
Characteristics of the orchards.

Apple variety	No. of block by apple variety				No. of Blocks	Number of permanent workers	Total hectares
	Granny	Fuji	Gala	Red			
Type of Harvest	selective picking	selective picking	selective picking	selective picking			
Orchard 1	0	4	5	0	9	5	57.3
Orchard 2	2	4	9	5	20	11	109.6
Orchard 3	4	5	8	5	22	16	156.9
Orchard 4	1	2	1	0	4	2	20.2
Orchard 5	1	1	0	0	2	3	37.5
Orchard 6	7	0	3	0	10	4	29.2
Total	15	16	26	10	67	41	410.7

the harvest of apples (*Malus domestica*) is seasonal and presents high variability in fruit yield, varieties, type of harvest, and quality (González-Araya et al. 2015).

The apple harvest is carried out in about three months. In the Southern Hemisphere, the harvest season begins approximately at the end of January and finishes at the end of April. This planning horizon may seem long; however, each apple variety cannot be harvested in a time window greater than fifteen days. Within these days, there is an optimal harvest window that lasts around five days. If the fruit is harvested outside these five days, it will suffer rapid quality deterioration (firmness, Brix degrees, color). Therefore, orchard managers seek to plan the harvest of each variety within their optimal time window. Nevertheless, this is not always possible since the necessary workers for carrying out the harvest are not always available. This situation causes loss of fruit quality and, consequently, the possibility to export them. According to Català et al. (2013), there are three possible market destinations for apples: export, domestic, and industry (juice, dehydration). Apples for export have the best quality in terms of appearance and, for this reason, have the best price. Apples destined for the domestic market are of intermediate quality while the remainder is industrialized.

The apple trees in the orchards are planted in different blocks that differ according to the planted apple variety, tree age, and block density. It is important to note that every block of the studied apple orchards is composed of around 11% to 30% of pollinating trees. In addition, the blocks of Gala and Fuji apple varieties must be harvested by selective picking. On the other hand, the blocks of Red and Granny Smith apple varieties must be harvested by strip picking. More details about apple harvest planning can be found in González-Araya et al. (2015).

The characteristics of each orchard of the studied company are shown in Table 4. This table also describes the type of harvest necessary for each apple variety, that is, if a variety requires selective picking or strip picking. The apple varieties that are harvested by selective picking usually require two selective pickings and a final strip picking. Thus, apples harvested during selective picking are destined for export, while apples harvested during strip picking are destined for the domestic market or for industry. The varieties that are harvested only by strip picking correspond to varieties in which all the fruit achieves the conditions to be exported at the same time. Therefore, the remaining fruit in a block of these varieties is harvested and destined to the domestic market or for industry. Table 4 also shows the total hectares of apple trees and the number of permanent workers in each orchard. This table corresponds to the following input information presented in Table 1 and shown in Fig. 1: “Number of orchards” (B) and “Number of blocks in each orchard” (C).

In Table 4, 67 blocks are analyzed with a total of 410.7 hectares. In this regard, it is important to mention that in Chile only 1.1% of fruit producers have more than 200 hectares and approximately 0.1% have more than 500 hectares. Therefore, the agricultural company where the data were collected is one of the largest in the country. This means that the study is a large-scale case for the Chilean fruit industry.

In addition, many of the blocks also have a pollinating variety that presents a different harvest window. For this reason, the blocks were divided into two sets of data, treating them as if they were two independent blocks. In this way, each block is considered as a block with the predominant variety and another one with the pollinating variety, giving a total of 124 blocks to analyze. In Table 5, it is possible to note that only 10 blocks have no pollinating variety, that is, only one set of data were considered (predominant variety) for theses blocks. For example, this is the case of blocks 4, 8, and 15 from orchard 2.

For harvest planning, a 64-day horizon was considered, which approximates the apple season. Table 5 shows, for the six apple orchards, the estimated kilograms of fruit to be harvested as well as the first day of each harvest window. This information is also sorted according to the type of harvest (selective picking or strip picking), apple varieties (Granny Smith, Fuji, Red, and Gala) and kind of variety (predominant or pollinating). In this table, the following colors represent a specific variety, green (Granny Smith), blue (Fuji), yellow (Gala), and red (Red). The information presented in this table corresponds to the inputs described in Table 1 and illustrated in Fig. 1: “Kind of fruit varieties planted in each block” (D), “Harvest window for each variety in each block” (E), and “Estimated fruit quantity during the harvest planning horizon for each variety in each block” (F).

Table 6 shows the estimated percentage of fruit that could be lost each day of the harvest window for not having the required maturity conditions. This fruit lost depends on the type of harvest and represents the fruit that would be lost if it were harvested on the corresponding day. These percentages were estimated by the agronomists in charge of the orchards according to the last fruit counting that took place approximately three weeks before the beginning of the season. These percentages are the same for each variety. For example, if the apple harvest is carried out on the first day of the harvest window of a selective picking (SE-P1 or SE-P2), 95% of the fruit would be without the required conditions. Whereas, if it is done on the sixth day of this period, only 5% of the fruit would be without the required conditions. Regarding the fruit harvested by strip picking (ST-P), the percentage of fruit lost remains constant at 10% during the five days that this type of harvest lasts. Table 6 adds the input information related to fruit quality of the “Estimated fruit quality during the harvest planning horizon for each variety in each block” (F) mentioned in Table 1 and illustrated in Fig. 1.

Table 7 presents the parameters used for modeling the case study, which do not depend on the type of harvest. In this table, the resources for mechanical harvesting are not presented since all the orchards were harvested manually in this case. In addition, the daily capacity of the processing plants remains constant throughout the season for both kinds of fruit destinations (export and do-

Table 5
Estimated apple harvest and first day of the harvest window according to each variety.

Orchard	Block	Predominant	Pollinating	Estimated harvest (kg)					First day of the harvest window				
				Predominant			Pollinating		Predominant			Pollinating	
				SE-P1	SE-P2	ST-P	SE-P1	ST-P	SE-P1	SE-P2	ST-P	SE-P1	ST-P
1	1	🟨	🟦	22,114	34,751	6,318	7,661	851	1	6	11	50	60
	2	🟨	🟩	126,062	198,097	36,018	198,149	22,017	1	6	11	33	43
	3	🟨	🟦	70,954	111,500	20,273	27,607	3,067	1	6	11	50	60
	4	🟨	🟦	35,837	56,315	10,239	113,301	12,589	1	6	11	50	60
	5	🟨	🟨	68,977	108,392	19,708	316,180	35,131	1	6	11	1	11
	6	🟦	🟩	16,456	25,859	4,702	4,023	447	45	50	60	33	43
	7	🟦	🟨	87,018	136,742	24,862	26,636	2,960	45	50	60	1	11
	8	🟦	🟩	82,903	130,277	23,687	84,181	9,353	45	50	60	33	43
	9	🟦	🟩	69,033	108,480	19,724	65,227	7,247	45	50	60	33	43
2	1	🟨	🟩	45,376	71,305	12,965	16,670	1,852	1	6	11	33	43
	2	🟨	🟩	99,031	155,620	28,295	56,653	6,295	1	6	11	33	43
	3	🟨	🟩	78,204	122,893	22,344	15,977	1,775	1	6	11	33	43
	4	🟨	⬜	12,576	19,762	3,593	-	-	1	6	11	-	-
	5	🟨	🟩	35,455	55,716	10,130	15,616	1,735	1	6	11	33	43
	6	🟨	🟩	36,565	57,460	10,447	100,311	11,146	1	6	11	33	43
	7	🟨	🟩	63,310	99,488	18,089	28,533	3,170	1	6	11	33	43
	8	🟨	⬜	10,318	16,215	2,948	-	-	1	6	11	-	-
	9	🟨	🟥	100,763	158,341	28,789	16,606	4,416	1	6	11	21	31
	10	🟥	🟩	71,548	-	7,950	39,747	4,416	21	-	31	33	43
	11	🟥	🟩	84,586	-	9,398	61,779	6,864	21	-	31	33	43
	12	🟥	🟩	410,839	-	45,649	63,367	7,041	21	-	31	33	43
	13	🟥	🟨	38,396	-	4,266	5,593	621	21	-	31	1	11
	14	🟥	🟩	178,780	-	19,864	29,905	3,323	21	-	31	33	43
	15	🟩	⬜	5,604	-	623	-	-	33	-	43	33	43
	16	🟩	🟥	667,105	-	74,123	58,235	6,471	33	-	43	21	31
	17	🟦	🟨	120,625	189,553	34,464	34,615	3,846	45	50	60	1	11
	18	🟦	🟨	31,813	49,992	9,090	8,985	998	45	50	60	1	11
	19	🟦	🟩	188,769	296,636	53,934	73,253	8,139	45	50	60	33	43
	20	🟦	🟩	110,998	174,425	31,714	40,226	4,470	45	50	60	33	43
3	1	🟨	🟩	19,752	31,039	5,643	10,120	1,124	1	6	16	33	43
	2	🟨	🟩	37,044	58,211	10,584	47,995	5,333	1	6	16	33	43
	3	🟨	🟩	64,640	101,577	18,469	41,761	4,640	1	6	16	33	43
	4	🟨	🟩	34,684	54,504	9,910	25,096	2,788	1	6	16	33	43
	5	🟨	🟩	123,958	194,791	35,417	125,027	13,892	1	6	16	33	43
	6	🟨	🟥	116,830	183,590	33,380	31,797	3,533	1	6	16	21	31
	7	🟨	🟩	151,776	238,505	43,365	221,967	24,663	1	6	16	33	43
	8	🟨	🟦	91,967	144,520	26,276	50,851	5,650	1	6	16	50	60
	9	🟥	🟨	388,955	-	43,217	36,577	4,064	21	-	31	6	16
	10	🟥	🟩	84,578	-	9,398	39,594	4,399	21	-	31	33	43
	11	🟥	🟩	158,064	-	17,563	23,198	2,578	21	-	31	33	43
	12	🟥	🟩	30,174	-	3,353	11,453	1,273	21	-	31	33	43
	13	🟥	🟩	178,102	-	19,789	52,327	5,814	21	-	31	33	43
	14	🟩	🟥	263,593	-	29,288	26,309	2,923	33	-	43	21	31
	15	🟩	⬜	18,569	-	2,063	-	-	33	-	43	-	-
	16	🟩	🟥	180,875	-	20,097	20,143	2,238	33	-	43	21	31
	17	🟩	⬜	60,648	-	6,739	-	-	33	-	43	-	
	18	🟦	🟩	46,253	72,684	13,215	16,331	1,815	45	50	60	33	43
	19	🟦	🟩	15,275	24,004	4,364	5,553	617	45	50	60	33	43
	20	🟦	🟩	160,342	251,966	45,812	177,017	19,669	45	50	60	33	43
	21	🟦	🟩	6,412	10,075	1,832	3,178	353	45	50	60	33	43
	22	🟦	🟩	108,317	170,212	30,948	144,049	16,005	45	50	60	33	43
4	1	🟨	🟩	43,061	64,592	11,961	13,254	1,473	1	6	16	33	43
	2	🟦	🟩	68,180	102,270	18,939	66,193	7,355	45	50	60	33	43
	3	🟦	🟩	90,344	135,517	25,096	104,711	11,635	45	50	60	33	43
	4	🟩	🟩	178,951	-	19,883	21,428	2,381	33	-	43	33	43
5	1	🟩	⬜	167,610	-	18,623	-	-	33	-	43	-	-
	2	🟦	⬜	10,037	15,056	2,788	-	-	45	50	60	-	-
6	1	🟩	🟥	119,457	-	13,273	1,248	139	33	-	43	21	31
	2	🟩	⬜	26,597	-	2,955	-	-	33	-	43	-	-
	3	🟩	🟥	189,839	-	21,093	6,187	687	33	-	43	21	31
	4	🟩	🟥	225,872	-	25,097	1,029	114	33	-	43	21	31
	5	🟩	⬜	31,796	-	3,533	-	-	33	-	43	-	-
	6	🟩	🟥	163,222	-	18,136	1,198	133	33	-	43	21	31
	7	🟩	⬜	1,286	-	143	-	-	33	-	43	-	-
	8	🟨	🟩	30,666	45,999	8,518	20,620	2,291	1	6	16	33	43
	9	🟨	🟩	31,288	46,932	8,691	17,758	1,973	1	6	16	33	43
	10	🟨	🟩	9,930	14,895	2,758	1,975	219	1	6	16	33	43

Table 6
Percentage of apple loss according to the type of harvest.

Day		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Type of harvest	SE-P1	95	90	70	55	40	5	5	5	5	5	10	20	40	50	60
	SE-P2	95	90	70	55	40	5	5	5	5	5	10	20	40	50	60
	ST-P	10	10	10	10	10										

Table 7
Parameters used for modeling the case study.

Parameters	Value
Hiring cost of a permanent worker (US$/worker)	14.98
Dismissing cost of a permanent worker (US$/worker)	37.46
Hiring cost of a temporary worker (US$/worker)	4.49
Dismissing cost of a temporary worker (US$/worker)	7.49
Bin capacity (kg)	380
Penalty cost for harvesting fruit without the maturity conditions (λ) (US$/kg)	0.13
Penalty cost for additional day of harvest (β) (US$/day)	0.0015
Minimum amount of fruit to be harvested (kg)	1
Maximum number of temporary workers per orchard	250
Processing capacity of fruit for export (kg/day)	3000,000
Processing capacity of fruit for the domestic market (kg/day)	3000,000
Cost of idle workers (US$/worker day)	19.70

Table 8
Productivity and labor cost used in the case study.

Type of Harvest	Productivity (kg/day)	Cost US$/day
Selective picking	1691	35.98
Strip picking	2307	19.70

(*) Observed dollar: 667.41 Chilean pesos (Thursday, October 20, 2016) Source: Central Bank of Chile.

mestic consumption). The input information from this table corresponds to the following items described in Table 1 and shown in Fig. 1: “Maximum number of available workers of each type” (I), “Costs of manual harvest” (L), “Estimated cost of fruit loss” (N), and “Bin capacity according to each fruit variety” (O). It is important to notice that Table 7 does not include all the “Costs of manual harvest” (L), which also involve labor cost. This cost is presented in Table 8.

The data presented in Table 7 were obtained from the analyzed agricultural company. The penalty cost λ was estimated in order to prioritize the harvested fruit with the required maturity parameters over the total harvest costs. In this way, an efficient frontier (Pareto frontier) was constructed. This frontier represents the trade-off between the kilograms for harvesting fruit without the maturity conditions and the total costs of harvest. Thus, the value of λ corresponds to the total costs of harvest associated with an extreme point of the Pareto frontier when the kilograms for harvesting fruit without the maturity conditions are at a minimum. On the other hand, the penalty cost β was estimated in order to prioritize the harvested fruit with the required maturity parameters and the total harvest costs over the reduction of the harvest days so that the orchard managers would not lose the quality of the harvested fruit. For this purpose, the weight method described by Gass and Saaty (1955) for linear bi-objective problems was used. Thus, the value of β corresponds to the limit cost without worsening the harvested fruit with the required maturity parameters and the total harvest costs.

The productivity and labor costs shown in Table 8 were obtained from the orchard managers. This information corresponds to the items “Productivity rate of each type of workers” (J) and “Costs of manual harvest” (L) described in Table 1 and illustrated in Fig. 1. As mentioned previously, the labor cost must be added to the cost of hiring and dismissing permanent and temporary workers as well as the cost of idle workers in order to obtain the “Costs of manual harvest” (L). For this case study, it was assumed that the productivity and daily labor costs of permanent and temporary workers were equal. In addition, it was assumed that there is no difference in respect to the productivity and daily labor cost for the same type of harvest, independently of the analyzed block.

The case study was solved using an exact method of the IBM ILOG CPLEX Optimization Studio 12.5 software and a heuristic method that corresponds to the GRASP metaheuristic presented in Section 4. This metaheuristic was implemented using NetBeans 8.0.2 software. Both methods were executed on a personal computer with an Intel Core i5–2410 M processor, 3 Gb of RAM, and 500 Gb of hard disk.

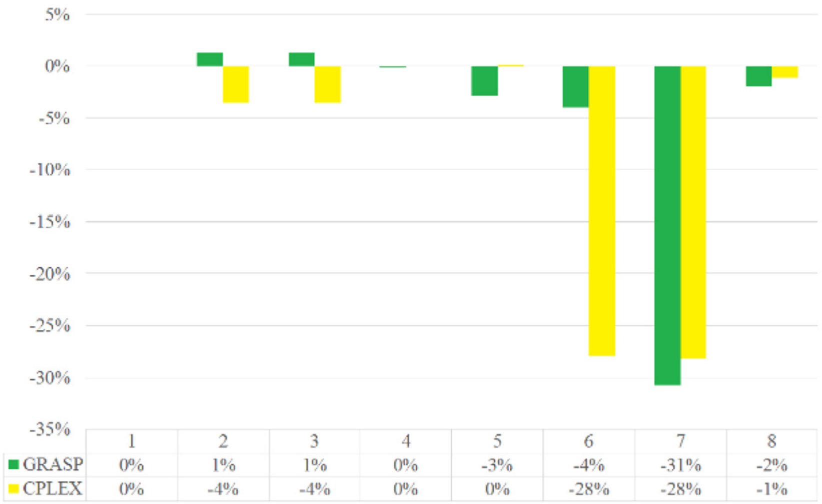
In this case study, two situations were evaluated considering the six orchards. One situation assumed that labor was not be shared among the orchards (case 1), while the other situation assumed that the six orchards share labor (case 2). The total execution time using the GRASP metaheuristic was 62 s for case 1, obtained by adding the running times for each of the six orchards. The execution time of the metaheuristic for case 2 was 292 s. The computational time increase for case 2 occurred because the computational time of the constructive and local search methods was not linear according to the increase in the orchards' size. The increase in orchard size had a greater impact on computational time than the decision about whether to share labor. On the other hand, for case 1, the execution time required by CPLEX for solving the six instances associated with each orchard was 16,200 s (4.5 h). In these instances, an average GAP (see Eq. (42)) of about 0.4% was obtained when a stop criterion of 3600 s was used as a maximum execution time for each instance. The execution time used by CPLEX for solving case 2 was 28, 800 s (8 h) and the associated GAP was 0.31%. In this case, a stop criterion of 28,800 s was established as a maximum execution time. Clearly, the GRASP metaheuristic for both cases demanded much less computational time than CPLEX.

The GAP of CPLEX is calculated according to the following equation (Berthold, 2013):

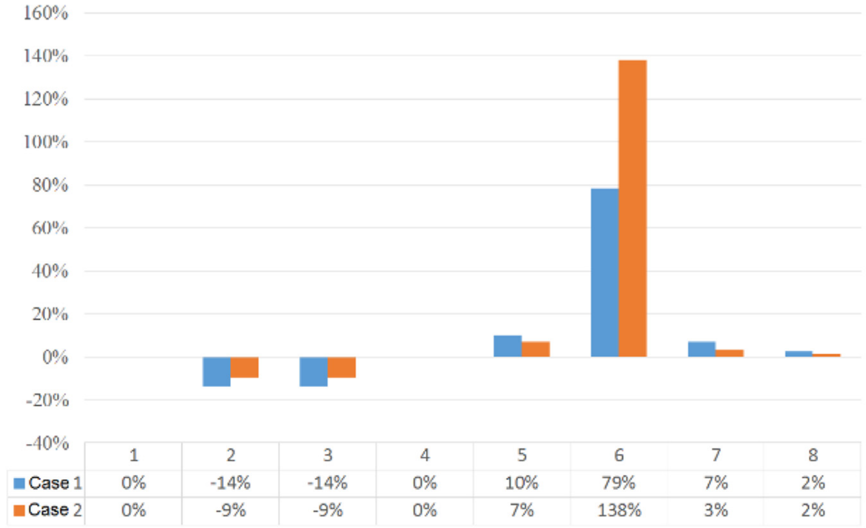
$$GAP = \frac{UB - LB}{UB} \tag{42}$$

Where LB corresponds to the lower bound of the relaxed solution obtained by CPLEX and UB represents the upper bound of the best integer solution obtained by CPLEX.

Regarding the quality of the obtained solutions, a comparison between those obtained by the GRASP metaheuristic in respect to those obtained by CPLEX is shown in Fig. 3.a. It shows the percentage difference between each cost item from the values obtained in case 2 to those obtained in case 1 for both the GRASP metaheuristic and CPLEX. Fig. 3.b shows the percentage difference between each cost item using the values obtained by the GRASP metaheuristic compared to those obtained by CPLEX for both case 1 and case 2. Each bar represents a cost item of the objective function, where 1 represents the costs of hiring and dismissing permanent workers (Z_2); 2 represents the costs of hiring temporary workers (Z_3); 3 represents the costs of dismissing temporary workers (Z_4); 4 represents the salaries of permanent and temporary workers ($Z_5 + Z_6$); 5 represents the costs associated with har-



a) Percentage difference between each cost item usingthe obtained values in case 2 compared to those obtained in case 1



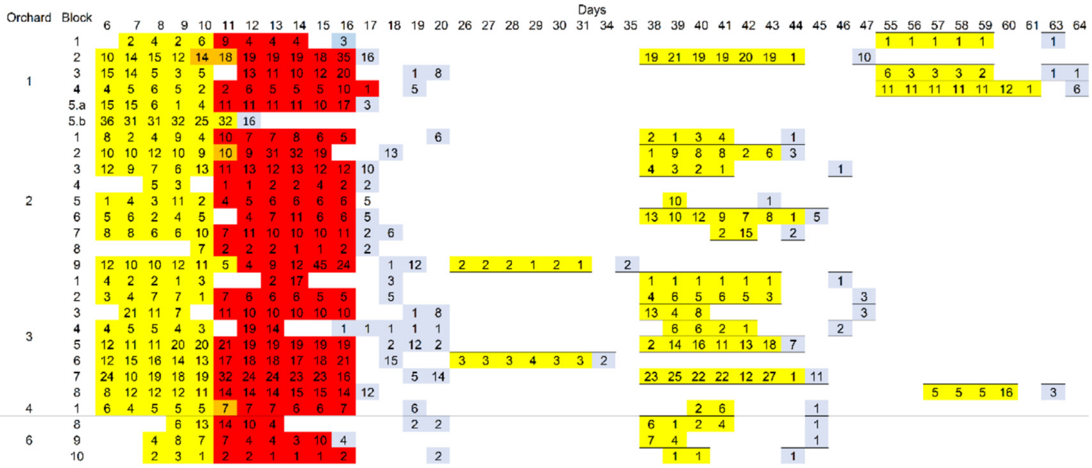
b) Percentage difference between each cost item usingthe obtained values fromthe GRASP metaheuristic compared to those obtained with CPLEX

Fig. 3. Percentage difference between each cost item.

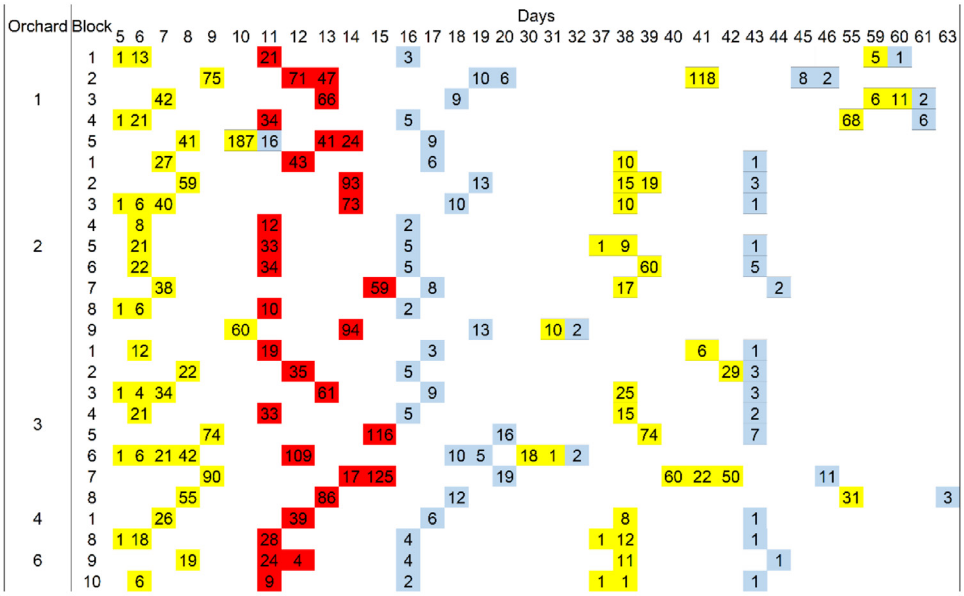
vesting fruit without the required maturity conditions and unharvested fruit in the orchards (Z_8+Z_9); 6 represents the costs related to compacting the harvest schedule (Z_{10}); 7 represents the costs of keeping idle permanent workers (Z_7); and, finally, 8 represents the total costs of the objective function.

In Fig. 3.a, it is possible to observe that when the GRASP metaheuristic is used, the total costs of case 2 is 2% lower than case 1. On the other hand, when CPLEX is used, this decrease is around 1%. The reduction of total costs with GRASP and CPLEX is obtained mainly because of a decrease in costs associated with idle workers (see bar 7 in Fig. 3.a). This situation occurs because permanent workers are assigned to harvest other orchards if they are idle. In Fig. 3.a, it is also possible to observe a decrease in the costs associated with fruit harvested without the required maturity conditions (see item 5 of Fig. 3.a). This fact implies that a greater amount of fruit may be exported and, consequently, producers may receive more income. On the other hand, there is an increase in costs for hiring and dismissing temporary workers. This fact occurs because permanent workers are assigned more efficiently during the harvest season, which causes temporary workers to only be hired when the harvest cannot be carried out by permanent workers. Therefore, temporary workers will be hired and dismissed more frequently during the season.

Fig. 3.b shows that, for both cases (1 and 2), the GRASP metaheuristic yields a total cost approximately 2% higher than that obtained by CPLEX. The greater percentage difference is observed for the cost related to the harvesting calendar compaction (item 6), which is 79%; however, this cost represents less than 1% of the total cost structure. On the other hand, the costs associated with the fruit harvested without the required maturity conditions (item 5) have a percentage difference of 10% between GRASP and CPLEX; these costs represent around 25% of the total cost structure. In summary, the GRASP solution yields slightly higher costs than those obtained by CPLEX. However, the CPLEX solution yields a little more fruit for export than the GRASP solution; therefore, producers could receive a slightly higher income. The extra kilograms



(a) GRASP harvest schedule



(b) CPLEX harvest schedule

Fig. 4. Harvest schedule and number of workers obtained for the Gala variety.

of fruit that could be exported in a harvest season were 58,262 kgs, which corresponded to 0.37% of the total kilograms produced during a season.

Fig. 4 is an example of how the output information “Worker assignment to each block” (S) and part of the “Tactical harvest plan for orchards” (Q), described in Table 1, could be represented. Figs. 4.a and 4.b show the harvest schedule for the Gala variety when labor is shared (case 2) when obtained by the GRASP and CPLEX, respectively. We can observe the harvest schedule and the total number of workers assigned daily to each block of this variety. For example, in Fig. 4.a, block 1, day 6 has no workers assigned, while in the same block and day, Fig. 4.b shows 13 assigned workers. In these figures, yellow represents the first selective picking of a block and red represents the second selective picking; light blue corresponds to the final strip picking. Orange means that the first and second selective picking are carried out at the same time, for example, block 2 of orchard 1 in the GRASP harvest schedule (days 10 and 11). The horizontal black lines located at the top and bottom of a harvest day represents the harvest of the pollinating variety. It can be observed that the harvest of pollinating trees starts from approximately day 26. When the harvest of the main and pollinating varieties occurs at the same time, the block is replicated twice. This situation occurs in block 5 of orchard 1 for the GRASP solution (Fig. 4.a), where block 5.a corresponds to the harvest schedule of the main variety and block 5.b corresponds to the harvest schedule of the pollinating variety. It is worth mentioning that the pollinating varieties for Gala could be Granny Smith or Fuji. The kilograms to be harvested and the number of bins required daily for each block are presented in Figure A.6 and Figure A.7 of the Appendix, respectively.

When comparing the harvest schedule represented in Fig. 4.a and Fig. 4.b, it is possible to observe that the CPLEX solution is more compact than the GRASP solution. This situation is consistent with the greater GRASP costs related to the harvest schedule, which are observed in item 6 of Fig. 3.b. The obtained harvest schedules are understandable for the orchard managers, allowing them to carry out the harvest plan.

6. Managerial insights

The developed GRASP metaheuristic and its results were presented to the operations managers and agricultural engineers of two agri-industrial companies in order to validate the proposed harvest planning and execution of the metaheuristic. These professionals highlighted the following advantages:

i) Harvest plan is obtained a long time in advance: This is a positive aspect since, as mentioned previously, usually the agri-industrial companies need to establish the contracts of the outsourced services for carrying out the harvest plan at least two months in advance (for example, transport, processing plants, refrigerated storage, labor, among others). This means that having a harvest plan in advance will facilitate contract negotiation and will probably reduce harvest costs. Additionally, an early harvest plan will help improve the coordination of later stages of the FSC.
ii) Shorter time for preparing the harvest plan: Currently, the harvest plan can take up to three weeks to prepare and sometimes not all the operational constraints are considered. For example, occasionally the upper limit of the plant capacity is not respected, which causes congestion and high waiting times for trucks in the fruit receiving area. On the other hand, the GRASP metaheuristic can find a feasible solution in a few minutes, which means that all the operational constraints are satisfied in the obtained solution.
iii) Greater flexibility for analyzing hypothetical situations: Due to the metaheuristic's speed, it is possible to analyze many possible scenarios in a short time by simply changing the entered values of the metaheuristic data in order to evaluate their impact on the harvest plan and to anticipate decisions.

An additional improvement of the GRASP metaheuristic mentioned by the professionals was that the data and information for planning the harvest must be stored jointly. Currently, the information is stored separately in different files and on several personal computers or in printed reports. As described in Section 2, the relationships among each kind of information is strong and the decision-making process is completely interrelated. Consequently, the current way of independently managing information causes discoordination in the FSC. Therefore, storing all the data jointly allows a faster and more efficient decision-making process. On the other hand, the professionals of the agri-industrial companies were a little concerned about obtaining all the necessary information for running the GRASP metaheuristic because it would require a greater effort and coordination among all the professionals involved in this decision-making process.

7. Conclusions

In this study, we propose an optimization model to support fruit tactical harvest planning that consider multiple orchards or farms and shared resources (workers). We addressed a common problem for large fruit exporting companies during a harvest season. With this purpose in mind, we developed a MILP model that sought to minimize the costs of harvesting, fruit lost for not reaching the required maturity, and the number of the harvest days. When this model was solved by an exact method (CPLEX) using large instances (over 60 blocks to be harvested), the optimal solutions were not achieved before the time limit of 3600 s. Moreover, the complexity for obtaining an optimal solution increased as the number of blocks to be harvested by workers increased. For this reason, it was necessary to develop a GRASP metaheuristic in order to facilitate the implementation of the model in fruit exportation companies.

A case study, which corresponds to a real case of a Chilean exportation company, was solved assuming two scenarios. The first scenario assumed that resources (labor) were not shared and the second that resources were shared. These two scenarios were analyzed to establish if the orchards' joint planning of resources would allow a cost reduction. In this way, it was observed that the total costs decreased around 2% when resources were shared; the greatest reduction was observed in the cost for maintaining idle permanent workers. When comparing the solutions obtained by CPLEX and by the GRASP in these two scenarios, it was observed that the largest difference corresponded to the harvest duration of each block. CPLEX proposed a shorter harvest duration than the metaheuristic. Regarding the costs, the GRASP metaheuristic yielded an increase of around 2% in the costs associated with the fruit being harvested without the required maturity conditions. On the other hand, the metaheuristic required much less computational time to obtain a solution than CPLEX, and its objective function was around 2% higher than that obtained by CPLEX. In this sense, the metaheuristic is more practical than CPLEX for solving problems. Finally, the proposed schedule provides the orchard managers the necessary information for planning the whole harvest season, as well as enabling them to do a proper monitoring and control of the harvest plan. Moreover, they could better coordinate with other stakeholders of the FSC.

For future research, it would be interesting to implement the GRASP metaheuristic in a decision support system (DSS). In this way, decision makers of agricultural companies could easily use it. Moreover, the DSS could be integrated with forecasting models in order to obtain a better estimation of the harvest window and the amount of fruit to be harvested. Therefore, it is also necessary to improve existing forecast methods for future research. Currently, the estimation error of each orchard yield is around 15%.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ejor.2020.08.015.

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