Applying Mathematical Programming to Planning Bin Location in Apple Orchards

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Abstract: In Chile, it has been observed that there is downtime during the apple harvest season. This is largely due to the long distances that the workers must cover and the lack of bins in the orchards. Currently, the administrators do not use methods that enable them to estimate the number of bins required or where they should be located. Taking these observations into consideration, this research paper proposes a plan for bin placement in apple orchards by applying a location model with the objective of diminishing distances covered by the harvest personnel. With data from an orchard in the Maule Region of Chile, the number of bins to be used is calculated taking into consideration the particular surface characteristics of the plantation and the apple variety maturity indicators. For the spatial distribution of the bins, the capacitated p-median was used, because better results were obtained with it in terms of reducing travel distance during the harvest and the ease of implementing the solutions.

1 INTRODUCTION

The Chilean apple industry has had a dynamic development which has placed Chile among the five main apple exporters worldwide with 10% of the market participation, equivalent to approximately 760,000 tons exported (Bravo, 2013). Currently, one of the major challenges facing this industry is to increase its leadership which requires better planning and coordination in all stages of the supply chain. However, in the Chilean fruit industry the supply chain activities are mainly based on the experience of its participants.

In the literature, the first authors to use mathematical programming models to support apple orchard management decisions were Willis and Halon (1976). Their research developed a dynamic programming model to determine the optimum mix of apple varieties to be planted over the long term and applied it to an apple orchard in Massachusetts, USA.

Other models developed for planning the fruit industry supply chain were presented by Ortmann et al. (2006), Masini et al. (2007), Masini et al. (2008), Catalá et al. (2013) and Munhoz and Morabito (2014).

In a related line of research, Ahumada and Villalobos (2009) carried out a literature review focused on models based on agricultural harvests for planning supply chain production and distribution of agro foods. Other literature reviews on mathematical programming models to support agricultural supply chain decisions can be found in Weintraub and Romero (2006) and Bjorndal et al. (2012), who dedicated a portion of their research to models in the agricultural area; Higgins, et al. (2010), who discussed the challenges of adopting operations research models in the agricultural value chain; and Shukla and Jharkharia (2013), who classified the models used in the fresh produce supply chain in various ways (country, year, problem context, technique used, among others).

Several mathematical programming models developed in Chile to support harvesting stage decisions have been applied mainly to the forestry industry (Palma and Troncoso, 2001, Troncoso et al., 2002)

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Among the fruit harvest planning in Chile, the well-known research by Ferrer et al. (2008) proposed a mixed integer linear programming model to determine the plan for grape harvesting which would minimize operating costs and maximize grape quality. In later research done by Bohle et al. (2010) they incorporated data uncertainty into the model presented by Ferrer et al.(2008)which was dealt with by robust optimization.

Regarding location model application to agriculture, Lucas and Chhajed (2004) carried out a review of location models based on territorial balance theory and optimal location applied to improving the agricultural supply chain. Found among the research done after that of Lucas and Chhahed (2004), is the work by Rantala (2004) who developed a mixed integer programming model in order to design a production-distribution system in the seed and seedling supply chain for the purpose of evaluating the expansion or closure of facilities (greenhouses and cold storage).In another study, Higgins and Laredo (2006) used two location models to improve the sugar value chain. One of these models is a p-median problem (Hakimi, 1964) which has an additional restriction that limits the largest average distance from the fields to the loading points. The other model is similar to the capacitated clustering problem (Osman and Christofides, 1994) which divides the producing farms into groups and seeks to minimize the sum of the distances from each farm to the center of the group. These models were applied to a sugar producing region in Australia. In a recent study, Srinivasan and Malliga (2013) applied a p-median model to locate collection centers for Jatropha seeds to be used to produce oil for biofuel. The purpose of the model was to minimize distances from the collection centers to the demand points, thus facilitating logistics for the growers.

In a previous study on bin location in apple orchards, González-Araya et al. (2009) proposed improving their distribution by using the capacitated p-median model (Hakimi, 1964, Garey and Johnson, 1979). This study extends the research by González-Araya et al. (2009) by taking into consideration the fruit maturity indicators according to variety, and also including information about the pollinating varieties. These new data permit better adapting to the orchard characteristics, thus obtaining a different bin distribution plan for each variety. In this manner, this research proposes to improve the bin distribution in apple orchards by applying a location model in order to reduce distances covered by the seasonal workers during fruit harvest. The model used is the capacitated *p*-median (Hakimi 1964).

Next, the problem of bin distribution in apple orchards is described. In Section 3 the mathematical formulation of the model and the parameters used are presented. In Section 4 a case study is described for an orchard located in Chile and in Section 5 the main results and discussion thereof are shown. Finally in Section 6 the conclusions and future research are presented.

2 DESCRIPTION OF THE PROBLEM

The pome fruit harvest involves extensive surface areas, and for this reason the orchards are divided into sections. In this manner, each section may have its own particular characteristics, these being: Fruit variety; plantation density (distance between trees in the same row and distance between rows); density (low, medium, high), that refers to the number of trees per hectare; year of plantation; area (hectares per section); type of irrigation; pollinating trees; among others. All these characteristics make it so that each section can be worked in an independent manner (Catalá et al., 2013). Moreover, pome fruit harvest is characteristically seasonal; with the season beginning once the ranges of maturity for each variety have been reached. In Chile, the harvest generally begins in mid-February and ends around mid-April; however, this can vary according to the climatic conditions each year.

The surface area planted with apples in Chile is about 37,297 hectares where the main producing regions are the Maule Region with 22,488 hectares and the O'Higgins Region with 10,011 hectares, uniting 87% of the national apple plantation surface area (Bravo, 2013).The Maule Region is the main apple producer in Chile with 60.3% of the planted surface area nationally, where 18,863 hectares correspond to red apples and 3,625 hectares to green apples (Bravo, 2013).Orchards in this region present an average density of 1,100 trees per hectare for red apples and 933 trees per hectare for green apples, and an average yield of 48.8 and 50.5 tons per hectare, respectively (CIREN and ODEPA, 2013).

The harvest requires seasonal workers, bins in which to put the fruit, harvest equipment (ladders, baskets, among others) and tractors to transport the bins. Coordinating resources during the harvest is a complex process, where the lack of any one of them can slow it down and affect the quality of the fruit.

The apple harvest in Chile is carried out manually to avoid any mechanical damage, given that the destination markets are very far away (Asia, the United States, Europe and the Middle East). Bins with a capacity of approximately 350 kilograms placed between the rows of trees are used to collect the apples in the orchard. The placement of the bins is done according to the preferences of the tractor driver with little coordination with those responsible for the orchard sectors. On one hand, the drivers know the number of bins that should be distributed in a given section and the harvesters know which rows of apples they should harvest. However, the way in which the bins are distributed results in either a scarcity or an excess of them among the rows. As well, the seasonal workers must frequently relocate the bins as they advance through the harvest sector. This generates down time and a number of extra hours for the tractor driver to collect the bins from the orchard.

3 MATHEMATICAL FORMULATION AND PARAMETER ESTIMATION

In this study the solutions from the capacitated p-median model (Hakimi, 1964, Garey and Johnson, 1979) are analyzed, for the purpose of establishing a bin location plan that would reduce travel distance for harvest crews and that the plan would be easy to implement.

3.1 Capacitated p-median Problem

In general terms, the problem consists of determining where to locate the bins and assign apples to each bin, minimizing the distance covered by the workers during the harvest. This case can be modeled as a capacitated p-median problem (Hakimi, 1964, Garey and Johnson, 1979). Thus, the installations or medians correspond to the bins and the demand areas correspond to the apples to be harvested.

In formulating the capacitated p-median model the following nomenclature is considered:

$N = \{1,...,n\}$ the set of possible bin locations within the sector

$M = \{1,...,m\}$ the set of apple trees in the sector

d_{ij} the linear distance between the apple tree i, $i \in M$, and the possible location of the bin j, $j \in N$.

p the number of bins needed in the sector

k the maximum number of apple trees that can be assigned to a bin,

The decision variables of the model are defined in the following manner:

$y_j \in \{0,1\}$, where $y_j = 1$ if a bin is located in position j, $y_j = 0$; if not, $j \in N$.

$x_{ij} \in \{0,1\}$, where $x_{ij} = 1$ if apple tree i is assigned to the bin located in j, $x_{ij} = 0$; if not, $i \in M$, $j \in N$.

Thus, the formulation of the capacitated p-median model is as follows:

$$\text{Minimize} \sum_{i=1}^{m} \sum_{j=1}^{n} d_{ij} x_{ij} \quad (1)$$

s.t.

$$\sum_{j=1}^{n} x_{ij} = 1, \quad i \in M, \quad (2)$$

$$\sum_{i=1}^{m} x_{ij} \leq k y_j, \quad j \in N, \quad (3)$$

$$\sum_{j=1}^{n} y_j = p, \quad (4)$$

$$y_j \in \{0,1\}, \ j \in N, \quad (5)$$

$$x_{ij} \in \{0,1\}, \ \forall i \in M, j \in N. \quad (6)$$

The objective function (1) seeks to minimize the sum of the distances covered by the harvesters from each apple tree to each assigned bin. The set of restrictions (2) guarantees that each apple tree be assigned to a single bin, while the set of restrictions (3) assures that a bin located in j can be assigned, at the most, to k apple trees. The restriction (4) establishes that p bins must be located. Finally, restrictions (5) and (6) define the variables that must be binary.

3.2 Estimation of Parameters Used in the Model

The model parameters are calculated in agreement with the description of the problem given in Section 2; those being: distance between an apple tree and the possible bin location points; number of bins to be located in each sector; capacity of each bin (measured in trees), which differs according to apple variety; and plantation characteristics by sector, that is, the number of trees planted and fruit count before harvest.

The potential bin locations are represented as discrete points established midway between apple tree rows and equidistant among the trees. The quantity of potential locations will depend on the plantation density, the distribution of pollinating trees and quantity of trees per row of surface area.

The distance d_{ij} (in meters) between apple tree i and the potential bin location j is obtained by calculating the Euclidian distance, given that it is a good approximation of the real distance covered by the harvest workers, since, generally there are no obstacles to covering the distance by walking in a straight line.

The parameter p indicates the number of bins to be located in a surface area to receive the gathered apples. Its value is determined with the following formula:

$$p = (PN_S / TA_S) \times (m / C_b) \times P_f \times F_a \tag{7}$$

Where:

PN_S: kg estimated net production for a sector.

TA_S: total trees of the variety to be harvested planted in a sector.

P_f: percentage of fruit on the tree with sufficient maturity for collecting.

C_b: Capacity of the bin selected for the harvest, measured in kg.

m: number of apple trees in the sector.

F_a: adjustment factor.

The adjustment factor permits defining a margin of security in order to avoid running out of bins during the harvest. In this case 1.1 was considered for the F_a. This value was obtained from the average of the variation coefficients in the production of the apple trees, which was 10%.

Once the p parameter has been obtained, the k parameter is calculated. It represents the quantity of trees it is feasible to assign to a bin when harvesting a particular variety so the unit of measurement is trees/bin. The formula is calculated as follows:

$$k = \left\lceil m/p \right\rceil \tag{8}$$

Formula (8) establishes that if the result is a decimal, it is rounded up to the next integer, given that k must be a whole number.

4 CASE STUDY

Data was taken from an orchard in the Maule Region, Chile that has an apple tree plantation of more than 66 hectares. The varieties of trees occupying the most surface area of the orchard were included, these being Royal Gala, Early Red One and Granny Smith. Each section of the orchard corresponds to the area where a specific variety is planted of which the number of hectares may vary. These sections present different types of harvesting; the Royal Gala is harvested by selective picking and the Early Red One and Granny Smith are harvested by strip picking. As is described by Gil (2004), in selective pickings, the sector must be covered at least three times during the season since the fruit does not mature homogeneously. In strip picking, the sectors are covered only once, harvesting all the fruit from the trees.

The instances of the location models were solved using the optimization software, CPLEX 12.0, academic version, for integer linear programming problems.

To generate the parameters of the capacitated p-median model it is necessary to obtain information about the characteristics and production of the sectors, which has to be periodically revised, and also data about the previous and current season. The required information for each sector is as follows: trees planted, surface area (in hectares), location of the pollinating trees, number of pollinating trees per sector and per row, plantation density, year of plantation, number of trees per row and per sector. The required data from the previous season include the kilograms of apples sent to a packing plant, kilograms of apples that did not meet the required quality parameters (discard), and the percentage of apples to be harvested. The necessary data from the current season are the tree load, the weight of the fruit in kilograms, the bin capacity in kilograms, an estimated percentage of apples that will not meet the required quality parameters (discard), and finally, the percentage of apples to be harvested.

In regard to the data from the previous season or that of the current season it is important to mention that both types of data are not used at the same time. One must select which of these information sources to use as input for generating parameters, taking into consideration the rigorousness of data collection in each of the seasons and the seasonal variability of the factors that affect the harvest (climatic conditions, fertilizer application, fruit thinning, fruit count, tree replacement, among others).

Applying the equations described in Section 3.1, the ranges and input parameters of the model for a sector are calculated with the obtained information. The capacity parameters and number of bins used in the model for each variety of apples is shown in Table 1, in which different harvesting methods are observed, and hence, different input parameters.

Table 1: Parameters used in the capacitated p-median location model according to apple variety by sector.

Variety	Harvest Method	Percentage of Harvest (%)	Bin Capacity (trees/bin) (*k*)	Sector Surface Area (ha.)	N° of bins to be located per sector (*p*)
Early Red One	Strip picking	100	9	4.5	685
Granny Smith	Strip picking	100	8	4.6	696
Royal Gala	Strip picking	100	7	6.4	848
Royal Gala	Selective pickings	80	8	6.4	680
Royal Gala	Selective pickings	60	10	6.4	508
Royal Gala	Selective pickings	40	14	6.4	336
Royal Gala	Selective pickings	20	28	6.4	181

5 RESULTS AND DISCUSSION

In this section the main bin distribution proposals obtained when applying the capacitated *p*-median model are presented. The results for the Early Red One and Royal Gala varieties that have the strip picking and selective picking methods, respectively, are described in greater detail.

With the information from the previous harvest season (2010) a plan for collecting according to sector was obtained, indicating the spatial distribution of the bins, and the distance between the bins (metric and practical).The practical distance is understood as the number of trees there should be between individual bins. It turns out that this distance is easier to explain to the tractor drivers who distribute the bins since it is only necessary to indicate the space (number of trees) that should be left between containers.

To estimate the harvest plan and the average distance covered by the seasonal workers in Sector M13 that has the Early Red One variety, the following information is used: 259,321 kg net weight harvested in the 2010 season, 379 kg average bin capacity and the strip picking harvesting method.

After applying the model, it was found that the average distance from the trees to their assigned bin covered by the harvest workers is 2.94 m, approximately. Considering the 119 rows in this sector, 685 bins should be located there in order to collect all of the apples.

Table 2: Bin location plan in the sector with Early Red One at 100% harvest.

Bin Location Plan					
Sector: Early Red One		Harvest method: Strip picking			
Between Rows		Number of bins	Number of apple trees	Metric distance	Practical distance
1	2	11	99	7.9	4
3	4	12	101	7.4	4
5	6	11	99	7.9	4
7	8	12	101	7.4	4
9	10	11	99	7.9	4
11	12	12	101	7.4	4
13	14	11	99	7.9	4
15	16	12	101	7.4	4
17	18	11	99	7.9	4
19	20	12	101	7.4	4

Part of the location plan obtained for harvesting the Early Red One variety which has a 4.5 ha surface area is shown in Table 2. For example, it is indicated on this table that 11 bins (second column) should be located between Rows 1 and 2 at a distance of 7.9 m (fourth column) or a practical distance of 4 trees (fifth column).As a reference, indicated in the third column is the total number of apple trees allotted to the 11 bins for Rows 1 and 2; that is to say, the 11 bins have the capacity to hold the fruit collected from the 99 apple trees between these two rows.

The difference between the metric and practical distance is about 6.2%, equivalent to 0.45m, so it is hoped that the use of the practical distance achieves an improvement similar to that of the metric distance.

In order to propose the bin distribution plan for Sector M4 which has the Royal Gala variety, the following information is used: 320,766 kg net weight harvested in the 2010 season, 386 kg average bin weight and 40% of the orchard production (a 40% selective picking).In this application of the capacitated *p*-median model the proposal described is for a 40% selective picking, which generally corresponds to the initial selective picking of the season. The total surface area of the plantation considered in this case is 6.4 ha.

According to the model results the seasonal workers must walk an average of 8.23 m from the apple trees to their designated bins.

Because of the contour level irrigation system used in the sector with this variety, it presents a different number of trees per row. For this reason, on occasion, locating only one bin between two rows was proposed. This situation is shown in Figure 1, where a bin is located between Rows 7 and 8, placing it at the end of the longest row. In this way this bin embraces a total of 27 apple trees at a distance of approximately 34 m or every 14 trees. Hence, to make the bin location operative, in each row a bin will be placed every 17 m or every 7 trees, which corresponds to the average distance between bins for a 40% selective picking (see Table 3).

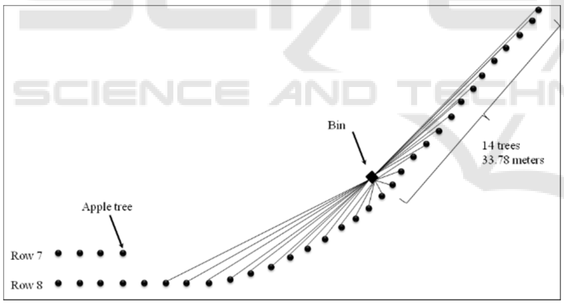

Figure 1: Bin location between rows 7 and 8 in the sector with the Royal Gala variety and the contour irrigation system.

The difference between the estimated metric and practical distances is 3.8%, equivalent to 0.65 m. As with the Early Red One variety, guiding the bin distribution using the practical distance is simpler for the tractor drivers.

For the bin location plans with different percentages of selective picking it was observed that the greater the percentage of selective picking, the lesser the average distance at which bins should be located. Following, Table 4 shows the results for apple varieties with a larger number of hectares planted in the orchard.

Table 3: Bin location plan for the Royal Gala variety at a 40% selective picking harvest.

Bin Location Plan					
Sector: Royal Gala			Harvesting method: 40% selective picking		
Between Rows		N° of bins	N° of Apple trees	Metric distance	Practical Distance
2	3	3	48	19.2	8
3	4	4	48	14.4	6
5	6	3	38	15.0	6
6	7	13	193	18.4	7
7	8	1	16	Locate at the end or beginning of the row	
	11	9	139	19.0	8
11	12	4	52	15.6	6
14	15	13	195	18.6	7
17	18	2	27	15.6	6
18	19	14	214	18.9	8
19	20	1	16	Locate at the end or beginning of the row	

Table 4 indicates how many bins are needed for the complete harvest in a determined sector according to the percentage of mature fruit, the bin location every certain number of rows and the distances between them determined by the number of trees.

It is worth mentioning that according to Gil (2004) it is recommended to do at least three selective pickings during the harvest season for the Royal Gala variety (sector M4), which implies covering the surface area planted with this variety three times. However, during the study season, only selective two pickings were carried out in the orchard for this variety; one 60% selective picking and the remaining 40% was harvested by strip picking. Thus, it is estimated that the location plan proposed for the 60% selective picking reduced the average distance covered by 0.46 m, implying a 5.73% reduction in the average distance covered. Similarly, for the 40% selective picking the average distance covered was reduced by 1.81 m, which means an 18.03% reduction in the average distance covered.

So, when the capacitated p-median model is applied, it is possible to reduce distances covered by the harvest personnel, where the average reduction is approximately 16%. This reduction in distances covered would allow improving the apple harvest productivity.

Table 4: Summary of the results for bin location according to apple variety by sector.

Variety	Sector	Percentage Harvested (%)	N° of bins to be located per Sector (p)	N° of rows between which bins are to be located	Average practical distance for locating a bin (number of trees)
Early Red One	M13	100	685	2	4
Granny Smith	M8	100	696	2	4
Royal Gala	M4	100	848	2	3
Royal Gala	M4	80	680	2	4
Royal Gala	M4	60	508	2	5
Royal Gala	M4	40	336	4	7
Royal Gala	M4	20	181	4	14

6 CONCLUSIONS

The capacitated p-median model was applied to the sectors of larger size in an orchard located in the Maule Region, Chile, where parameters representing the characteristics of each sector were used. Therefore, the model is flexible in that it adapts to the conditions in a specific surface area, taking into account different input sources. Moreover, it permits the use of various bin capacities, making it adaptable to other types of pome fruit harvest.

In this study a bin location plan was proposed for harvesting the Early Red One, Granny Smith and Royal Gala varieties, which resulted in a reduction in the average distance covered between the apple trees and their specific container of 16.48%, 28.38% and 11.88%, respectively. This reduction in the distances covered would permit an increase in worker productivity and a reduction in harvest operational costs. However, given that there was no study done on harvest times and associated costs, it was not possible to estimate these effects.

The suggested location model can be applied to the harvest of pollinating trees as well, considering these trees represent 11% of the plantation area.

The harvesting process reflects several opportunities for research intended to improve its operation. For example, the system used to determine the fruit load is not based on any statistical procedure to validate its reliability. Therefore, a study could be done based on the particular characteristics of each sector keeping in mind the respective maturity indicators (such as fruit color), and the associated agro climatic variables.

The plantation characteristics of each sector are important parameters to consider for the harvest so maintaining up-to-date information about these parameters is necessary for making good decisions. However, not all the orchards consistently carry out this activity. In the case of the study orchard, the exact distribution of the pollinating trees within a sector is unknown to the administration; they have only an estimated ratio of pollinating trees per sector, which is approximately 11%. According to what was observed for the analyzed varieties, the distribution of the pollinating trees depends on the variety planted in the sector. Also, it should be taken into account that the harvest of these pollinating trees does not occur at the same time as that of the main variety, which involves planning a different harvest in the same sector.

In future research it is recommended to study the operations involved in harvesting the pollinating trees with stationary bins and bin-carrying carts since it could improve the assignment of machinery for the harvest and reduce its cost. This is relevant since, as previously mentioned, the pollinating trees represent approximately 11% of the trees planted in a sector. Thus, for the largest sector in the orchard (sector M4) with 6.4 hectares planted with approximately 5,690 apple trees in all, the 11% pollinating trees corresponds to 626 apple trees which must be harvested. This illustrates the complexity of harvest planning for this sector. Moreover, this difficulty increases considering that during the season several sectors are harvested at the same time.

Finally, other research opportunities arise from the development of simulation models to plan the machinery needed for the harvest and the application of vehicle routing models for the purpose of minimizing distances and fuel costs for the tractors used for collecting and placing the bins in the orchard.

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