Supporting Harvest Planning Decisions in the Tomato Industry

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Abstract: Tomato is a raw material that easily deteriorates once harvested and loaded on trucks, losing juice and flesh. Therefore, the reduction of trucks' waiting times in the receiving area of a processing plant can allow reducing tomato waste. In this article, we develop a model that aims to keep a continuous flow of fresh tomato to a paste processing plant and to decrease trucks' waiting times in the plant receiving area. The model is used in a real case of a tomato paste company. The obtained solutions present a better allocation of the harvest shifts, allowing more uniform truck arrivals to the plant during the day. Therefore, trucks waiting times are reduced, decreasing raw material deterioration.

1 INTRODUCTION

The problem of trucks congestion in tomato processing plants is discussed, which causes high trucks' waiting times and deterioration of the transported raw material.

This problem is especially relevant in the competitive tomato industry, where the major world exporters, as USA and China, with 35% and 13% of world production, respectively, exert a strong prices pressure (ODEPA, 2013). In 2012, Chile ranked tenth in the export of tomato paste, with about 100 thousand tons exported per year. On the other hand, the main tomato paste consumers markets are located in Europe, Africa, Asia and Middle East, very far from Chile. Because of this, Chilean companies are constantly seeking to increase their productivity and reduce their production costs.

In the supply chain of tomato paste, the coordination between harvesting, transportation and production stages is necessary because of during a production season the plants work 24 hours. In this sense, a good coordination allows to obtain a continuous fresh tomato supply to the plants during the day, reducing trucks' waiting times and avoiding fresh tomato deterioration. Therefore, the productivity of raw material conversion is increased and so, the production and transportation costs are diminished.

Many researchers have addressed the supply chain planning and coordination of agrifood produce. Ahumada and Villalobos (2009), Díaz-Madroñero et al. (2015) and Soto-Silva et al. (2016) present reviews of optimization models that support decisions in different stages of the supply chain, and for different kind of agricultural products.

Related to harvest planning coordination, in the literature is possible to found a considerable number of articles devoted to the sugarcane industry (Higgins, 2006, López-Milán, and Plà-Aragonés, 2015, Pathumnakul and Nakrachata-Amon, 2015, Lamsal et al., 2015, Lamsal et al., 2016, among others). However, these models are usually specific to each country and industry, because of differing levels and different infrastructures of vertical integration, as specified by Lamsal et al. (2016).

In their work, Higgins (2006) and Lamsal et al. (2015, 2016) present optimization models that aim to reduce trucks' waiting times.

Higgins (2006) presents a mixed integer programming model, which deals with the trucks congestion problem in the sugar mills of Australia. The model seeks to minimize the trucks' queue time and the sum of the mills' idle time. This model has a high complexity, because of it also incorporates the generated queue in each each mill. For this reason, Variable Neighborhood Search (VNS) and Tabu Search algorithms are developed to solve it.

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Lamsal et al. (2015) propose an integer programming model that seeks to coordinate the harvest and transport of sugarcane supply chain in order to reduce trucks waiting times. For achieving this goal, the proposed model maximizes the minimum gap between two successive arrivals in a sugar mill.

Lamsal et al. (2016) propose a model to plan trucks movement between harvest and plants. This model is applicable when there are multiple and independent producers and it is not convenient to store fresh produce in the place of the harvest. The methodology used by these authors is divided in two stages. In the first stage, a model to determine the harvest start times is run. In the second stage, an algorithm for determining the number of trucks to transport raw materials is executed.

In this research is applied a version of the model developed by Lamsal et al. (2016), using data from a Chilean company. The company requires a tool for supporting decision to determine start times of tomato harvesting machines and the number of trucks to assign in each farm, every day. In this way, the company can guarantee a continuous flow of raw materials to the plants and to reduce trucks' waiting times and the tomato deterioration.

Therefore, this paper is structured as follows. In Section 2, the description of transport and harvest problem is presented. In Section 3, the proposed mathematical model for determining daily harvest start times of each tomato farm is explained and, in Section 4, a case study of the tomato paste company is carried out. Finally, in Section 5 the conclusions as further research are presented.

2 HARVEST PLANNING AND TRANSPORT TO A TOMATO PROCESSING PLANT

In agribusiness, companies generally ensure their plants' supplies by purchasing fresh raw materials from different suppliers, located in areas as near as possible to the plants. For this reason, before the harvest season, the companies make contracts to purchase all the yield of the suppliers' farms. This behaviour is also observed in the tomato industry.

In the harvest season, the tomato harvesting machines are outsourced and they move to each farm according to the harvest plan established by the company.

As the tomato harvesting activities, the fresh raw material transport from the harvest sites to the processing plants is also outsourced.

Every day, the selection of tomato farms to be harvested is performed according to the information about tomato ripening in each field and the daily demand of each plant. The trucks allocation to the farms depend on each transport contractor, which has assigned one or more harvesting machines. The contractor is responsible for determining which truck will transport fresh tomato to a plant, based on the number of daily truckload per harvesting machine estimated by the company. In general, it does not exist a decision support system for carrying out this activity.

Each company determines the working hours of tomato harvesting machines, but it is very common that companies have fixed shifts during the day. Most harvesting machines are used during the morning and the afternoon that involves high trucks demand in these periods.

Once a truck arrives to the receiving area of a plant, a download code is assigned to it. Subsequently, it is weighed and recorded at the gathering place, where trucks wait their shift to the next stage. Once the plant requires its fresh raw material, the truck goes to the quality control process, where the percentage of damage is determined based on a sample of 20 kilograms. Finally, the truck is directed to a defined placement area where it proceeds to unload the tomato.

The plants operate 24 hours every day, therefore, they require a continuous flow of raw material and, consequently, a continuous flow of trucks. However, because of work shifts established for the farms are mainly concentrated during the morning and the afternoon, the truck arrivals to the receiving area of the plants are concentrated from the afternoon. This situation causes trucks congestion, so each truck waits in the receiving area on average four hours. This problem involves an increase of transportation costs due to the number of hours spent by trucks in the receiving area and implies a tomato deterioration during waiting time, because of juice and flesh loss.

In Table 1, the effect of waiting times decrease for a constant level of production is shown. It is possible to observe that a decrease in one hour of waiting times, for a same level of production, reduces in 85.4 tons the plant raw material requirements. These data were obtained from a Chilean company that manufactures tomato paste.

Table 1: Effect of waiting times in tomato deterioration.

Decrease in the waiting time (hour)	No. kg tomato per kg tomato paste	No. ton of tomatoes	Daily savings (ton)
0:30	5,42	3.004,6	40,8
1:00	5,34	2.960,0	85,4
1:30	5,25	2.912,5	132,9
2:00	5,16	2.861,7	183,7
2:30	5,06	2.807,8	237,6

In this sense, in order to improve the supply efficiency, the development of a model to plan operations for both, harvest and transport activities, is necessary, aiming to obtain a constant flow of trucks during the day, to decrease the trucks waiting times at the receiving area of plants and so, to reduce raw material deterioration.

3 MODEL FOR HARVEST PLANNING

The following sets are used in the model:

C_i: set of loads at farm i, i ∈ I, j ∈ C_i.

I: set of farms to be harvested.

The parameters considered by the model are the following:

n: number of blocks of time in which the day is divided.

a_k: start time of the block k, for k= 0, 1, …, n. Furthermore $a_0 < a_1 < a_2 \ldots < a_n$, where a_n represents the end time of the delivery window.

h_i: time required to harvest a load at farm i, i ∈ I.

N_k: unloading capacity in the plant for each block k=0, 1, …, n-1.

t_i: travel time between farm i and the plant, i ∈ I.

α: penalization associated with the deviation of the plant's unloading capacity.

lmt: maximum number of farms that can be harvested in shift 3.

The decision variables of the model are the following:

x_{ij}: arrival time at the plant of *i*th farm's *j*th load, i ∈ I y j ∈ C_i.

y_i: time when the harvesting starts at farm I, i ∈ I.

λ_{ij}^k: ∈ R+ and expresses the instant in which the *j*th load of the *i*th farm lies between the time a_k and a_{k+1}, i ∈ I, j ∈ Ci and k= 0, 1, …, n.

b_{ij}^k: ∈ {0,1}, where b_{ij}^k = 1 if the *i*th farm's *j*th load arrives between a_k and a_{k+1}, b_{ij}^k = 0 otherwise.

CS_k: surplus capacity or positive deviation from the plant's unloading capacity, k= 0, 1, …, n-1.

CF_k: slack capacity or negative deviation from the plant's unloading capacity, k= 0, 1, …, n-1.

MX_i: ∈ {0,1}, where MX_i = 1 if the shift 3 is available to be assigned in the farm i, MX_i = 0 otherwise.

The formulation of the proposed model for harvest planning is presented in this section. The indices, parameters and decision variables of the model can be founded in the Appendix.

Mathematical formulation

$$\text{Min } Z = \sum_{k=0}^{n-1} (\alpha * CF_k + (1-\alpha) * CS_k) \quad (1)$$

s.t.

$$x_{ij} = y_i + j * h_i + t_i \quad \forall i \in I, j \in C_i \quad (2)$$

$$x_{ij} = \sum_{k=0}^{n} (\lambda_{ij}^k * a_k) \quad \forall i \in I, j \in C_i \quad (3)$$

$$\sum_{k=0}^{n} \lambda_{ij}^k = 1 \quad \forall i \in I, \quad j \in C_i \quad (4)$$

$$\lambda_{ij}^0 \le b_{ij}^0 \quad \forall i \in I, \quad j \in C_i \quad (5)$$

$$\lambda_{ij}^k \le b_{ij}^{k-1} + b_{ij}^k \quad \forall i \in I, j \in C_i, \; k \in 1, \ldots, n \quad (6)$$

$$b_{ij}^n = 0 \quad \forall i \in I, j \in C_i \quad (7)$$

$$\sum_{k=0}^{n} b_{ij}^k = 1 \quad \forall i \in I, j \in C_i \quad (8)$$

$$\sum_{i \in I} \sum_{j \in C_i} b_{ij}^k + CS_k - CF_k = N_k \quad \forall k \in 0, \ldots, n-1 \quad (9)$$

$$b_{ij}^k \in \{0,1\} \quad \forall i \in I, j \in C_i, k \in 0, \ldots, n \quad (10)$$

$$\lambda_{ij}^k \in [0,1] \quad \forall i \in I, j \in C_i, k \in 0, \ldots, n \quad (11)$$

$$CF_k, CS_k \ge 0 \quad \forall k \in 0, \ldots, n-1 \quad (12)$$

$$y_i \ge 0 \quad \forall i \in I \quad (13)$$

$$x_{ij} \ge 0 \quad \forall i \in I, j \in C_i \quad (14)$$

The objective function minimizes positive and negative deviation from the plant's unloading capacity. Depending on the case can be penalized just one of the deviation or more heavily in one direction than the deviation on the other side. For example, to achieve a high utilization of the plant should be penalized the slack capacity ($\mathrm{CF_k}$) and to minimize the downtime of the trucks should be penalized specially the surplus capacity ($\mathrm{CS_k}$).

Constraint (2) states that the arrival time at the plant of *i*th farm's *j*th load depends on the harvest start time in the farm i, the harvest rate at that farm and the travel time between the farm and the plant. Constraint (3) – (8) determine the arrival time through a convex combination of the beginning and the end time of each block into which the arrival falls.

Constraint (9) determines the slack or surplus capacity in each block by comparing the quantity of inputs with the unloading capacity.

Finally, the constraints (10) – (14) stablish the nature of the decision variables.

4 CASE STUDY

In this section the model is used in a real case, which is based on data from a tomato paste company.

This company has two production plants, where annually 550,000 tons of fresh tomato are processed. The raw material is purchased from different farmers and it is daily harvested using 40 tomato harvesting machines. These harvesters are mostly subcontracted and assigned to the farms according to the percentage of tomato ready to be harvested in each one (from 90% of ripe tomato). For this assignment is used a manual scheduling.

The company works with three work shifts, which start at 07:00, 13:00 and 17:00 hours; shifts 1, 2 and 3, respectively. In addition, its plants operate 24 hours a day. In order that the model assigns to the harvesting machines these times, the function (15) is established. It is important to mention that 7 hours are subtracted from the schedules with the aim of working with values between 0-24.

$$y_i = \begin{cases} 0:00 \\ 6:00 \\ 10:00 * MX_i \end{cases} \quad \forall \mathrm{i} \in \mathrm{I} \qquad (15)$$

At the same time, because it is difficult to harvest at night (shift 3), a binary variable ($\mathrm{MX_i}$) and restriction (16) is defined. Thus, the total number of shifts 3 assigned to the harvesters is restricted.

$$\sum_{\mathrm{i} \in \mathrm{I}} MX_i \leq lmt \quad \forall \mathrm{i} \in \mathrm{I} \qquad (16)$$

4.1 Dataset

To implement the model are used data of harvest from the season 2016 for one of the plants of the company. This plant is normally supplied for 12 farms.

Table 2 shows the data of the farms that supply the plant.

Table 2: Number of loads, travel time and harvest time from the farms that supply the plant.

Farm	Number of loads	Harvest time (hour)	Travel time (hour)
#1	9	1,1	1,6
#2	6	1,7	0,8
#3	10	1,0	0,3
#4	4	2,5	0,6
#5	3	3,3	1,5
#6	7	1,4	0,6
#7	8	1,3	0,3
#8	6	1,7	0,9
#9	6	1,7	1,1
#10	5	2,0	0,3
#11	9	1,1	0,3
#12	10	1,0	0,8

The case study was performed on an 2,40 GHz Intel Core i3 CPU running the Windows 10 operating system. The computational results associated to the case study are obtained using IBM ILOG CPLEX Optimization Studio version 12.6.

Three scenarios are solved, since the maximum number of work shifts 3 to be allocated is modified. The first run (case 1) uses the same proportion of harvesting machines in each shift that the company assigned on that day for the farms. With this, the goal is to determine the optimal distribution while maintaining the number of harvesting machines working on each shift. In the second run (case 2) is limited to a maximum of 25% of the farms to be harvested on shift 3. This equates to a maximum of three farms. Finally, in the third run (case 3) the amount of farms that can be harvested in shift 3 is not limited.

For all instances, the software takes less than 1 minute. It is noteworthy that, since it is a daily planning, are needed low runtimes software.

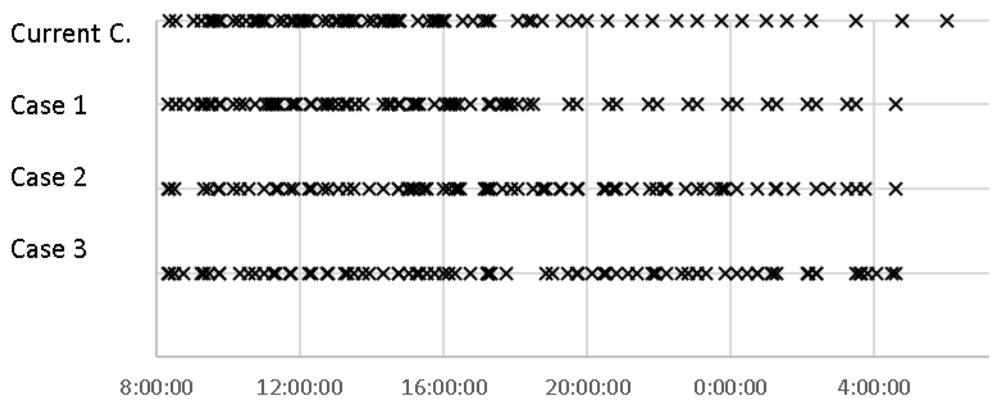

Figure 1: Distribution of arrivals during the day.

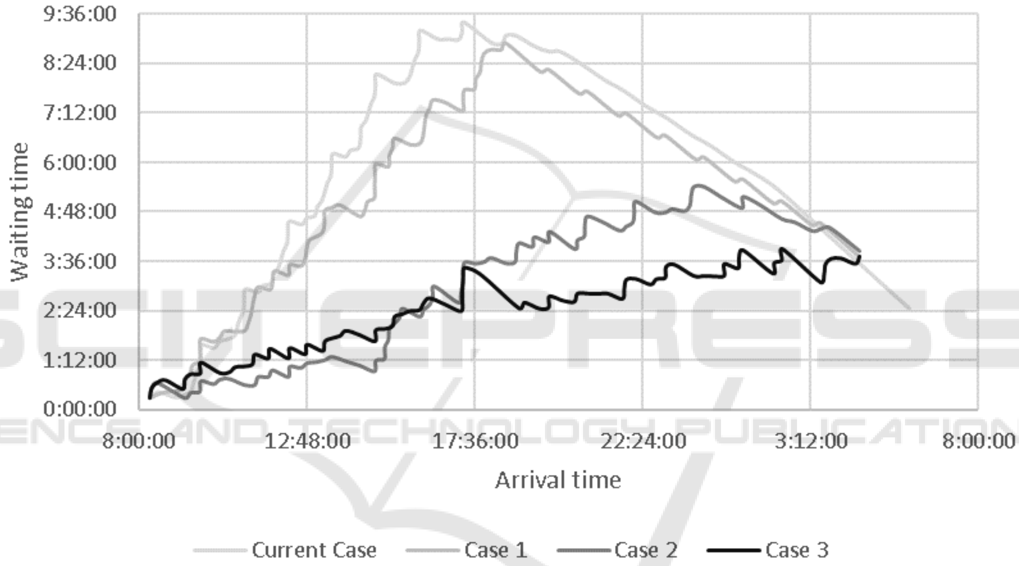

Figure 2: Waiting times per hour for each case.

4.2 Main Results

Table 3 compares the real shifts assigned to the farms with those obtained by the model. It can be seen that in the real distribution of harvesters (real allocation and case 1), the schedule most commonly used is the shift 1. On the other hand, the schedules for unrestricted modelled case (case 3) are spread more evenly between shift 1 and shift 3. This is based on that, a more even distribution of shifts during the day, allows more uniformity in the arrival of trucks and, consequently, of load and raw materials. Regarding the case with restriction (case 2), similar results are obtained to the real distribution (case 1). However, greater use of shift 2 and shift 3 is observed.

Table 3: Results for each case.

Shift	Real allocation and Case 1	Limited allocation in shift 3 (Case 2)	No limited allocation in shift 3 (Case 3)
#1	10	6	5
#2	1	3	1
#3	1	3	6

Figure 1 shows arrivals of trucks to the plant for each case. It can be seen that for the real case the most trucks arrive at the plant during 8:00 and 16:00 hours. For case 1, which considers the same proportion of harvesting machines in each shift that the real allocation, is observed a high arrival rate until about 19:00 hours. The allocation of work shifts, which are obtained for the optimization model for case 2, generate a more uniform distribution during the day compared to the two previous cases. Finally, arrivals associated to case 3 present a high uniformity.

In order to analyse the impact of the model solutions in improving the planning of harvest shifts, software Arena Simulation, version 14.7 is used to perform this analysis. The simulation allows to calculate waiting times and queues generated on the plants in each case.

Figure 2 shows waiting times of the trucks in plant in relation to its arrival time. The graph shows a significant decrease in waiting times for cases 2 and 3, compared to cases 1. It is important to note that, for example, the trucks arriving at 18:00 hours, based on the allocation of real case and case 1, must wait about 8 hours in the plant for the download process. With respect to cases 2 and 3, waiting times decrease considerably, obtaining a waiting on plant close to 3 hours at 18:00 hours.

Table 4 shows the average and maximum waiting times, as well as the number of trucks in queue for each case.

For case 1 are obtained average waiting times 4:51 hours, which represents a decrease of about 30 minutes compared to the real case. With respect to case 2 and case 3 it is obtained a considerable reduction in waiting times for trucks on plant compared to real case and case 1, yielding an average of 2:53 hours for case 2 and 2:22 hours case 3. With respect to the number of trucks that are in plant for the download process is obtained on average 8.5 trucks for case 2 and 6.9 trucks for case 3.

The implementation of the model in case 3 causes a decrease in waiting times of up to 3 hours compared to the real case. At the same time, the schedules that consider restrictions on the amount of farm that can be harvested in shift 3 (case 2) provide equally better results than manual planning. It is important to emphasize that the scenarios with constraints on shift 3 are more likely to implement in the operations of the company, since working during night hours is more dangerous because of the lack of light and because the night shifts are more difficult to manage and control.

Based on these results, it is possible to conclude that the use of the model allows to obtain a better allocation of the harvest shifts, which allows truck arrivals more uniform during the day and, therefore, shorter waiting times and a decrease in the deterioration of the raw material.

Table 4: Waiting times and trucks queued for each case, according to the simulation.

		Wait time (hour)	**Number of trucks in queue**
Current case	Average	5:22:00	16,2
	Maximum	9:23:12	33
Case 1	Average	4:51:42	13,2
	Maximum	8:54:14	26
Case 2	Average	2:53:35	8,5
	Maximum	5:23:33	18
Case 3	Average	2:22:47	6,9
	Maximum	3:52:55	13

5 CONCLUSIONS

The optimization model was used in a real case of a tomato paste company. In this application, three cases were analyzed. The first case use the same shifts' distribution established by the company (case 1). The second case allows only to allocate a maximum of 25% of the farms in the shift 3 (case 2). Finally, the last case does not limit the allocation of the farms in every shift (case 3).

The use of the model allows obtaining better shift allocation of harvesting machines, which improves the arrival distribution of trucks into the plants. The case 3, that does not limit the number of farms assigned to shift 3, presents the best harvesting machines allocation, which helps to reduce the trucks' waiting times in about three hours. However, this allocation is difficult to implement in any agribusiness company, because it requires that many farms be allocated in the evening or night shift (shift 3). In general, workers do not like be assigned at the last shift. Additionally, night shifts are difficult to manage and control.

For the other hand, the company can implement more easily the obtained solutions for cases 1 and 2. The model solution for case 1 distributes in a better way than the current situation, the farms and harvesting machines allocated in each shift. The solution for case 2, that allows an increase up to 25 percent of farms assigned to shift 3, is more feasible to be implemented by the company and shows a decrease of about 2:30 hours of trucks' waiting time.

According to these results, the impact of solutions implementation in the company could be high. If a decrease of about 2:30 hours of trucks' waiting time takes place, based on the data presented in Table 1, saving of around 237.6 tons of tomato could be obtained. Similarly, the obtained solution in case 1 could allow savings of 40.8 tons per day. In addition, reducing trucks waiting times in the plant could speed up the tomato supply and help to reduce the number of trucks required for transportation, causing a decrease of transportation costs.

The use of the model for assigning harvest shifts obtain better and faster results than the current allocation method utilized by the company. Moreover, the model execution requires little computational time for obtaining solutions, which is a necessary condition for a daily planning. For implementing the model, a following stage is to develop decision support system, so users could interact easily with the model entering data and parameters, and getting suitable harvest plan reports.

For future extensions of the model, it could be interesting to plan harvest activities for a longer period, as for example a week. This dynamic model could include the reduction of harvesting machines' shift changes that are not considered when a daily plan is executed. Furthermore, this new model extension could also minimize harvesting machines displacement during the period.

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