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Operational model for planning the harvest and distribution of perishable agricultural products

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ABSTRACT

This paper presents an operational model that generates short term planning decisions for the fresh produce industry. In particular, the application developed helps the grower to maximize his revenues by making production and distribution decisions during the harvest season. The main motivation for this model comes from the fact that the profitability of producers is highly dependent on the handling of short term planning in the harvest season. Some of the factors affecting profitability include the management of labor costs, the preservation of the value of perishable crops, and the use transportation modes that provide the best trade-off between time (quality of products) and cost. These issues are interrelated, and their judicious management is fundamental for attaining good financial results. The results of the proposed planning model indicate that significant savings can be obtained by managing the trade-off of the freshness at the delivery of the product with the added labor and transportation cost at the grower's side. Moreover the results also show that dynamic, information based, management practices might be preferred over traditional practices based in fixed labor allocation and distribution practices.

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1. Introduction

Growers of perishable agricultural products, such as fresh fruits and vegetables, very often face complex planning problems such as deciding the level of technology to use, how much of a particular crop to plant, the timing of planting and harvesting. The problem becomes even more complex if conflicting objectives are involved, for instance a grower could try to maximize total production, or minimize the labor used to grow and harvest the crops, or minimize the losses due to sending an over-ripe product to the market. From a traditional planning perspective the grower faces planning problems at different levels. For instance, the farm location and other infrastructure decisions can be considered strategic level planning problems. Those decisions that are made each year, such as the timing of planting and resource allocation among competing crops can be considered tactical level problems. Once the crop is planted and short term decisions are made regarding its cultivation, harvest and distribution; then operational planning is applied (Ahumada and Villalobos, 2009). In this context, the current paper aims to assist the farmer by providing him with a decision model that generates operational, short term, planning decisions. In particular, the operational model to be introduced assists in making production and distribution decisions during harvesting with the objective of maximizing the revenue obtained by the grower.

The main underlying motivation for developing a model that handles harvesting decisions is that the profits and losses observed by growers of fresh perishable crops are highly dependent on these short-term decisions. Among the most important issues in short-term harvesting planning are the management of labor costs, preserving the value of perishable crops, and using efficient transportation modes that provide the best trade-off between time to reach the market (quality of products) and cost. For example, the consumer demands that a certain quality attributes be present in fresh produce at the time of sale. However, to preserve these attributes the growers might incur in higher costs in terms of labor and transportation. This paper addresses this trade-off by developing a planning model that quantifies and balances the loss of value due to the persihability of the crops and the costs incurred to prevent that loss, such as increasing the number of harvests in a given time period.

To show the applicability of the proposed model, this paper presents a case study based on two products: bell peppers and tomatoes. These crops were selected because of their economic importance (Johnson et al., 2006) and their modeling complexity. Another advantage of using tomatoes in the case study is that the tools developed can be easily adaptable to other fresh crops such as cucumbers, and eggplants (Marcelis, 2001).

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The remainder of this paper is organized as follows: Section 2 presents a review of previous works related to operational planning of perishable agricultural products. Section 3 presents the main issues in modeling operational decisions for horticultural crops. Section 4 presents the operational model for planning the activities related to the growing and distribution of horticultural crops. Section 5 presents the results of the application to a case study. Finally Section 6 provides the conclusions and future research for this problem.

2. Literature review

Among the operational decisions made by the growers, harvesting, scheduling of production activities, storing, packing, and shipping are some of the most significant. Of these decisions, storage and harvesting are particularly important given the limited shelf life of these products (Ahumada and Villalobos, 2009). Since many agricultural activities remain labor intensive, another factor that needs to be considered in the operational planning of perishable crops is the use of labor (Zhang and Wilhelm, 2009).

Although operational planning is clearly important in the fresh food supply chain, there have not been many planning models or tools devoted to it, as highlighted by two recent reviews (Ahumada and Villalobos, 2009; Zhang and Wilhelm, 2009). Nevertheless, there is a growing awareness of the need of operational planning models that can quickly react to changing environments that cannot be predicted in advance and properly included during tactical planning (Thysen, 2000). We briefly discuss next some of the salient works in the area of operational planning in the supply chain of perishable crops.

One example of operational planning is given by harvesting models, which include decisions such as the amount of product to harvest per period, the transportation of the harvested product to the packing site, and the scheduling of packing and processing plants. The work by Ferrer et al. (2007) can be considered a good representative of the papers dealing with harvesting planning. This paper presents a mixed integer-programming (*MIP*) model for optimally scheduling the harvesting operations of wine grapes. The model considers the costs of harvesting activities and the loss of quality of the grapes for delaying harvesting. One of the main contributions of this model is the representation of the quality loss in the objective function of the model.

Other examples of operational models in the literature include those related to production–distribution, such as the work of Rantala (2004), who presents an MIP model for designing the integrated production–distribution plans for the seedling supply chain of a Finnish nursery company. Some of the decisions included in the model are the total number of seedlings to be produced and transported from nurseries to cooled warehouses, or transported directly to customers, or transported from warehouses to customers. The model also includes capacity constraints and capacity-related decisions. The main objective of the model is to minimize the total cost of producing and transporting the products needed to meet customers demand.

A finding that can be drawn from the literature reviews consulted (Ahumada and Villalobos, 2009; Zhang and Wilhelm, 2009) is that planning models dealing with perishable products very often fail to incorporate shelf life and stochastic features in the different echelons of the supply chain. Perhaps the reason for this lack of more realistic scenarios is the added complexity of finding solutions for the resulting models. In the few cases that reality-based stochastic features were introduced into the models the results justified the added complexity of the model (Jones et al., 2003; Allen and Schuster, 2004).

A common characteristic of most of the operational planning models that have been published is the lack of shelf life features in the majority of the models developed for planning perishables agri-foods. This is troubling since these features are essential for maintaining the quality and freshness of perishable products. One exception to this finding is the work of Rong et al. (2011) who present an optimization model for managing the quality of fresh food throughout the supply chain. This paper models the quality degradation of products, by time and temperature, as they pass through the supply chain in different facilities and transportation modes. The objective of the paper was to minimize production, transportation, storage, cooling, and disposal costs, while preserving the required quality and quantity demanded by customers.

From the existing literature consulted we conclude that although the agri-food supply chain is an area that is attracting a growing interest, there is a limited number of models addressing operational planning needs. This paucity of applications is especially evident in the case of integrated models that aim at planning more than one aspect of the agri-food supply chain. However, given the thin profit margins currently observed by the producers, there is definitely a need for efficient operational planning since it could make the difference between a successful and an unprofitable operation.

3. Problem description

One of the differences between tactical and operational planning for the harvesting and distribution of perishable crops, is that at the time that operational planning is applied growers have better estimates of the crops' yields and of the market conditions than when the tactical plans are prepared. However, even with the reduced uncertainty at the short term planning level, there are still uncontrollable factors influencing the decisions, such as sudden market fluctuations, the expected yield and maturity of the crops, which are highly dependent on weather conditions, and the postharvest behavior of the crops. Some of the factors affecting operational planning are shown in Fig. 1.

To deal with short term planning issues, a planning model should incorporate, along with the postharvest behavior of crops, the effects of weather, transportation time, postharvest decay, labor, and delivery costs. At the same time, the decision variables in the model should incorporate the transportation mode and harvest policy that would enable the crops to reach the right customer (higher revenue) at the right quality, with the appropriate remaining shelf life and with the proper routing through the food supply chain.

Fig. 2 presents a schematic of a generic supply chain for fresh produce to be used for the development of the planning model to be presented. While the details can vary from country to country,

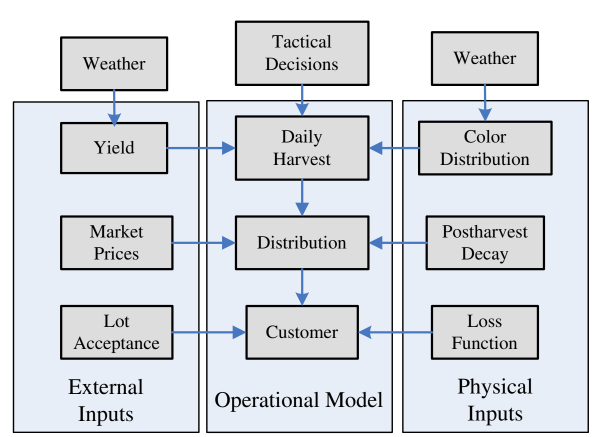

Fig. 1. Planning problem diagram.

we believe that the main factors involved in the distribution of fresh produce are captured in this schematic.

For instance, in the horticultural supply chain, crops can be contracted (sold before hand) or sold in the open or spot market. Very often the customers in the open market prefer to pick up their products free on board (*FOB*) at the warehouse of packers, while those who enter into contracts include delivery into the contract, and in-between there are a lot of different combinations of agreements, for storage and transportation requirements, as shown in Fig. 2.

Another issue that needs to be considered in the operational planning model is the final destination of the crops, since customers are becoming more specialized in their requirements. For example, in the case of tomatoes, there are different markets for different types of tomatoes such as mature green and vine ripe tomatoes. Mature green tomatoes are harvested before they reach maturity (every 2 weeks) and are ripen just before they are shipped. On the other hand, vine ripe tomatoes, are harvested at the breaker stage, which require 2–3 harvests/week. Usually fast-food restaurants prefer mature green tomatoes, while retailers prefer vine ripe (Calvin and Ciik, 2001). Thus growers need to balance market demands, with their cost and operational limitations, such tradeoffs, are among the many issues that need to be included in planning models.

The remainder of this section presents the main assumptions of the model and a detailed explanation of the factors considered in modeling the operational decisions in the fresh produce industry.

3.1. Assumptions and planning horizon

In the development of the operational model it is assumed that the tactical and strategic decisions, such as production planning (how much and when to plant) and logistic design, have already been made. This implies that at the time the operational model is applied, the decision maker has complete knowledge of the varieties and the quantities planted of each crop and the available transportation modes. It is also assumed that it is not possible to increase the production of crops at the operational planning level. Therefore, we assume that demand has to be satisfied from the crops available, or by acquiring additional products in the open market. Other resources fixed at the tactical level include the number of seasonal laborers hired for the remainder of the season

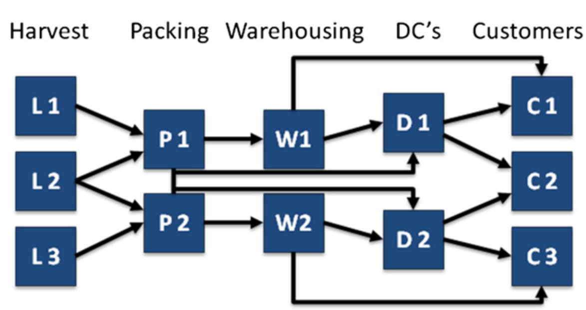

Fig. 2. Supply chain of fresh horticultural crops.

and the availability of day laborers. It is also assumed that there is historical data available about the yields and quality distributions of the crops planted.

With respect to the planning horizon, we propose a look-ahead horizon of 4 weeks for harvest, packing and transportation decisions. Such planning horizon implies a total of 12 harvesting and packing days available (Fig. 3), and another 12 days for storing and transportation. An example of how a planning horizon might appear is given in Fig. 3.

As it can be observed from Fig. 3, packing is usually performed concurrently with harvesting, with storage and or transportation quickly following. Furthermore, the planning horizon is expected to be applied under a rolling horizon updated at least once per week, if the planners require more accuracy; it could be updated twice or more per week (Miller et al., 1997).

3.2. Market uncertainties in the fresh produce industry

The limited shelf life of horticultural crops prevents their prolonged storage, forcing producers to supply demand with current production, regardless of the yield distribution of the crops. These supply restrictions cause the industry to under- and over-produce, creating marketing uncertainties that make the demand and pricing of produce harder to estimate. This behavior is evident in the case of the market for fresh tomatoes, where prices increase when supply is low (winter months) and decrease when supply is ample (summer months). Besides seasonal trends, tomato prices can also be highly variable along the harvesting season, with large peaks and valleys and sudden changes on these prices. There are even significant changes in prices from 1 week to the next, as it can be shown in Fig. 4. Which presents the daily prices of tomatoes collected by the USDA (2007) for the winter/spring season starting from the last 2 weeks of December to the last week of May.

These variations in the markets and their effects on the grower's income are what make short-term decision making increasingly important.

3.3. Yield and maturity of perishable crops

Two of the main inputs for the operational model are the yield and maturity of the crops during the harvest periods. Since the accurate estimation of the amount of fruit ready to be harvested and its particular quality characteristics are important to determine the frequency of harvest, transportation and marketing decisions. The proposed model integrates the estimates of yield and maturity of the fruits through the use biological models, developed by researchers in the agricultural sciences, which are described next.

From the perspective of growth and yield models, most of the research has been developed for greenhouse technology (Jones et al., 1991; Heuvelink, 1996), with limited applications aimed at open field production (McNeal et al., 1995). However, these models are difficult to apply in industry because of the large number of parameters and variables involved. Such limitations have also been mentioned as one of the restrictions for applying

Mo	Tu	We	Th	Fr	Sa	Su	Mo	Tu	We	Fr	Sa	Su	Mo
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Harvesting													
Packing													
Storage/Transportation													
Shelf Life													

Fig. 3. Planning horizon for the operational model.

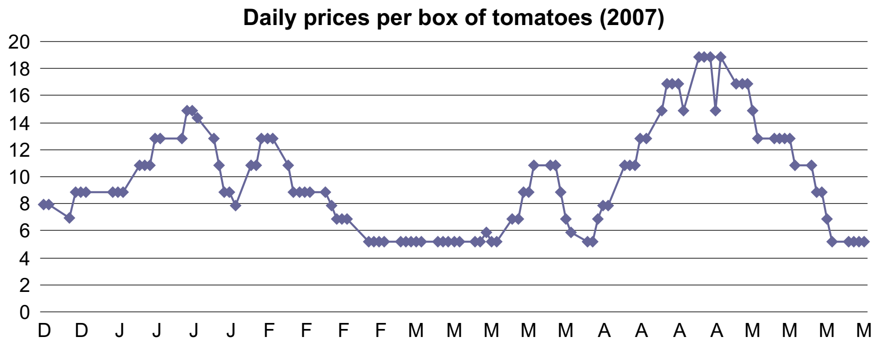

Fig. 4. Prices for the winter and spring season F.O.B. Nogales, AZ.

decision support tools for the optimal management of tomato crops (Lopez-Cruz et al., 2005). An alternative followed in the present research is to use historical information of weekly harvest to determine the expected volume to be harvested based on the time of planting. This information can be fine-tuned using weekly samples from each plot to arrive to an estimate of the fruits carried by the plants and the state of their maturity. Both pieces of information can be used to estimate the distribution of yields and the sizes of fruit for the following weeks.

From the perspective of fruit maturity, there are several models that have been used to estimate the maturity and development of tomato and other crops. According to the literature, the most important measures used to sample the quality of fresh produce are grade, shelf life, color, texture, and external appearance (Gary and Tchamitchian, 2001). For the case of tomatoes, two quality attributes are most relevant, color and firmness (Schouten et al., 2007a). In particular, color is used as an external index for firmness, shelf life and overall quality, and it is usually the preferred measure used on produce distribution companies (Tijskens and Evelo, 1994).

To determine the effects of harvesting decisions on the quality and freshness of the harvested crops, it is necessary to estimate the distribution of color classes for a given harvest policy. One way to estimate color development is by using functions that have been developed for predicting changes in the color of fruits through time (Hertog et al., 2004; Schouten et al., 2007b). These functions predict color development based in their color at the time of harvest (H_o) and the exposure of the fruit to ambient temperature (T).

One example of this type of function is the one proposed by Hertog et al. (2004) given by Eq. (1), which we apply in two different ways: (a) to determine the total shelf life of the products after-harvest, and (b) to estimate the effects of harvest frequency in the color distribution of the harvested crops:

$$H(t) = H_{\max} + \frac{H_{\min} - H_{\max}}{1 + (e^{kt(H_{\min}-H_{\max})}(H_{\min} - H_o)/(H_o - H_{\max}))} \tag{1}$$

$H_{\max}$ is the maximum color achieved at maturity (42.9). $H_{\min}$ is the minimum color at mature green stage (124). H_o is the color of the fruit at time of harvest. t is the independent variable in time (days). k is the temperature dependent constant ($k = k_{ref}e^{(Ea/R)(1/T_{ref}-1/T)}$). Ea is the energy activation, which is dependent on the variety (138,443). R is the universal gas constant (8.314 $\text{mol}^{-1}\,\text{K}^{-1}$). T is the constant environmental temperature of the stored fruit (in K) k_{ref}: rate constant of at an arbitrary reference temperature. T_{ref} is the reference temperature, which was selected to calculate k_{ref}.

In Hertog's methodology, the color results are given in hue angle, and it is necessary to translate this information so it can be used in the planning model. For our model we use the standard used in North America tomato ripeness, which consists of six stages (USDA, 1997): mature green (color 1), breaker (color 2), turning (color 3), pink (color 4), light-red (color 5), and red-ripe (color 6). The compatibility between hue color and the color scheme used in industry is shown in Table 1.

Table 1
Color classification scheme for tomatoes (Saltveit, 2005).

Stage of development	Hue	USDA
Mature green	115.00	1
Breaker	83.90	2
Turning	72.85	3
Pink	61.80	4
Light-red	48.00	5
Red-ripe	41.30	6
Over-ripe	37.00	6+

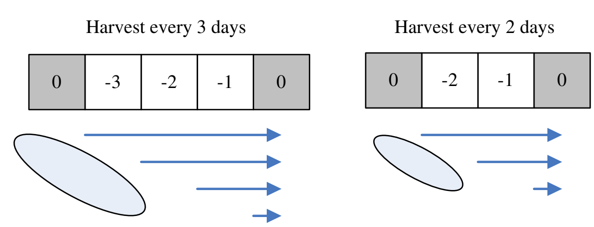

Fig. 5. Maturity of crops based on harvest frequency.

The color function (Eq. (1)) is used to determine the effect of harvest frequency decisions in the color distribution (maturity) of tomato fruits. Given that a common practice in the vine ripe tomato industry is to harvest all fruits at the breaker stage or above in the color scale, every time the crops are harvested, leaving on the field only mature green fruits at various stages of development. Because of this policy, the fruits collected will vary in their development, depending on the frequency of harvest, since there could be several days between one harvest and the next. For instance, given a harvest frequency of 2 days (right graphic of Fig. 5), it is expected that the fruits that were not picked in the previous harvest (day 0) will continue to mature resulting in a given distribution of colors for the next harvest based in the days already on the plant, the days elapsed since the last harvest (-1, -2) and the speed of growth induced by the environmental temperature. If the frequency decreases to harvest every 3 days, then the range of color distribution is expected to broaden, given that fruits have remained exposed to the temperature for a longer period of time, as it can be observed in the left-hand side of Fig. 5. This implies that the expected distribution of colors at the time of harvest is dependent on the frequency of harvest and the environmental conditions of the days before harvest occurs.

To estimate the color distribution of the fruits at the time of harvest, two approaches were tested: one that assumes the color distribution of the fruits at the plant follows a uniform distribution and another that assumes a normal distribution. The first approach is useful when no data is available for the output of harvested fruits, since the uniform distribution can be easily modified to fit different ranges of color schemes. On the other hand, if there is information available in the form of samples or from the packing data, then it is possible to estimate a distribution that relates better with natural systems, such as the normal distribution. For more details about these methods the reader is referred to Ahumada (2008).

3.4. Postharvest modeling of perishable crops

The third factor to consider at the operational level is the shelf life of the product once it has been harvested. In order to estimate the decay (or loss of value) of products during storage and distribution, adequate metrics are required for measuring the product quality. A related issue is the desired quality demanded by consumers and their acceptance behavior. Both of these aspects can be combined in the concept of keeping quality, which is the time until a commodity becomes unacceptable because certain quality attribute of the crops has deteriorated beyond the acceptance limit of customers (Tijskens and Polderdijk, 1996).

As mentioned before, the keeping quality of tomatoes is mainly dependent on the color development of the fruit when it reaches the customers. However, the development of the fruit color, under regular handling and storage circumstances depends in their initial maturity and the time and temperature during storage (Tijskens and Evelo, 1994). Usually tomatoes are harvested at the mature green or breaker stage (or higher), depending of their market target and the labor costs of the growers. Given these market conditions, growers must handle the tradeoffs between what the market demands and the labor costs from a higher harvesting frequency.

In order to balance the market preferences and the higher cost of labor, the color development of the crops was estimated by using the maturing function given in Eq. (1). To use this function, it was assumed that after-harvest, fruits were conserved at a constant temperature (e.g. temperature of 59 °F) throughout the distribution channels. Similar versions of this function have also been used to determine the acceptability of product batches based on the color development of the fruits (Hertog et al., 2004; Schouten et al., 2007a). Furthermore, the estimation of color development can provide a reasonable approximation for the behavior of tomato fruits through time, which can be used to determine the quality of tomatoes across the distribution chain.

An example of the estimation of color development is presented in Fig. 6, which shows the ripening process for a fruit harvested at the breaker stage and stored at a constant temperature of 59 °F. According to this model, it will take around 15 days for the fruit to reach the light-red stage, which is the common ripeness found at the retail markets. In order to incorporate color development into the operational model, two different methods based on a loss function accounting for the change in tomato color through time were developed. The first one is based in lot-sampling acceptance techniques for estimating the probability of rejection by the customer. The second function penalizes the lack of freshness of fruits by decreasing the value of crops through time. This function is explained in more detail in the description of the planning model in Section 4. For a more detailed explanation of this function the reader is referred to Ahumada (2008).

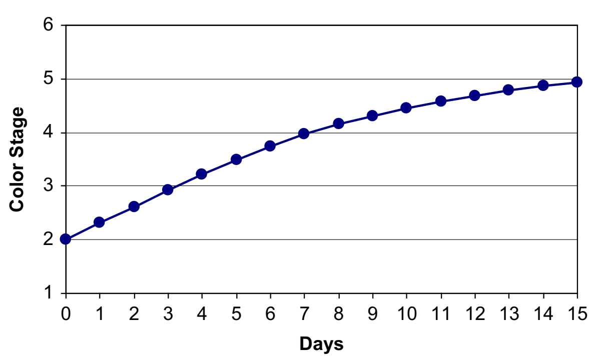

Fig. 6. Postharvest ripening of tomatoes (temperature 59 °F).

3.5. Logistics chain of perishable crops

The last major factor included in the operational model is the distribution requirements of customers in the produce supply chain. The distribution decisions in the operational model include packing, storage and transportation decisions. The aim of these decisions, from the perspective of the growers, is to supply the customers with the right product in the most profitable way.

As mentioned before there is a trade-off between the costs of storage and transportation and the quality of the crops delivered to customers. Furthermore, customers also impose service requirements, such as the maximum time for delivery or the immediate availability of products, which implies the storage of products closer to the customer. To support these distribution requirements, different type of resources are required, which include distribution centers and transportation modes (see Fig. 2).

The operational model assumes that, given the short-term decisions, it might not be feasible to send a large amount of product through some transportation link. For this reason, the model assumes a limited capacity of the transportation modes. In particular, the operational model assumes three types of transportation mode can be used to ship the products between the packaging plant and the final customers, or between the plant and the distribution centers. The transportation modes are trucking, railroad and air, which are the most common in North America, and the most popular modes of transportation for perishable products. For the operational model, the basic unit of transportation is given in containers, and it is assumed that all containers used in the three transportation modes are similar to the ones used in the trucking industry (48–53′). The remainder of the assumptions for transportation modeling is presented in the next section, together with the detailed operational model.

4. Operational model

This section provides a detailed description of the operational model designed for the harvesting and distribution of fresh horticultural products. As mentioned before the main decisions of this model include which products to harvest, their frequency (times per week) and the days they should be harvested. These decisions should consider time and labor restrictions, and the effects of harvesting decisions on the quality of the products. The model addresses these decisions by using predetermined patterns for harvesting a plot, for example a plot could be harvested, daily, three times per week, two times per week, etc. Even when there could be many different patterns, there exist a finite number of these patterns that could be used for commercial purposes for the proposed 12 day planning horizon in harvest decisions. Moreover once a pattern is selected it could be used for several weeks, depending on the market and environmental factors that influence the harvesting decisions.

The potential patterns for a 12 days harvest horizon are presented in Table 2, which shows the days selected for harvest with a harvest frequency between 1 and 4 days. For example,

Table 2
Patterns for harvesting a crop.

Pattern	Day											
	1 Mo	2 Tu	3 We	4 Th	5 Fr	6 Sa	7 Mo	8 Tu	9 We	10 Th	11 Fr	12 Sa
I	1	1	1	1	1	1	1	1	1	1	1	1
II	1	0	1	0	1	0	1	0	1	0	1	0
III	1	0	0	1	0	0	1	0	0	1	0	0
IV	1	0	0	0	1	0	0	0	1	0	0	0

pattern II has a frequency of three times per week (harvest every 2 days) and pattern III has frequency of two times per week. There are two patterns type II, three type III, and four type IV, which cover all of the 12 harvesting periods in the planning horizon.

One assumption made for the use of the patterns is that more than one pattern can be used for harvesting a plot in a given planning horizon. For example, half the plot can be harvested with pattern II starting at day 1 and the other half can be harvested with the same frequency as pattern I, but starting in day 2. Because of this formulation one part of a plot can be harvested in day 1 and the other part in day 2.

For the operational model, we chose to maximize the income of the grower, given a choice of customers, the prices they offer, and the costs incurred to serve them. We assume each contracted customer has a maximum demand (*DW*) and there is a limit on the total demand in the open market (*SWO*). The main costs in the objective function (Eq. (2)) are the cost of growing the crop (CF_j), transportation (e.g. CT_{fir}), harvesting (CH_j), packing (CK_k), labor (*Clabor*), storage (*CI* and *CID*), and delivery (*CTD* and *CTW*). The benefits obtained include the price paid by the customers (*PC*) and the revenue from the open market (*PN*). Given the structure of the model, the only time products are sold in the open market is when it is profitable to do so.

A major component of the objective function is the estimated cost from rejected or discounted shipments. This cost is determined in two ways, first by the probability (*PROB*) that the crop's color passes a determined threshold predetermined by the customer. A second one is penalizing the deterioration of the products along the chain by estimating the change in color (*COL*) from the time of harvest to the time it reaches the customer. For example, the function shown in the formulation penalizes with up to half the value of the products if the color reaches the higher level of maturity ($(6-2)/8=0.5$). However this function can be modified according to the preferred level of freshness required in the supply chain:

$$
\begin{aligned}
\max & \sum_{tki} PC_{tki}\left(\sum_{qfr} SC_{tkqfir}+\sum_{hqwr} SW_{htkqwir}+\sum_{hqdr} SD_{htkqdir}\right) \\
&+\sum_{tk} PN_{tk}\left(\sum_{hqw} SWO_{htkqw}\right)-\sum_{hpqf} CK_k\, QP_{hpqf}-\sum_{hqp\in P(j)}(CH_j+CF_j)\cdot QH_{hpq} \\
&-\sum_{tfir} NTI_{tfir}\, CT_{fir}-\sum_{twir} NTW_{twir}\, CTW_{wir}-\sum_{tdir} NTD_{tdir}\, CTD_{dir} \\
&-\sum_{tfwr} NTP_{tfwr}\, CTPW_{fwr}-\sum_{tfdr} NTK_{twir}\, CTPD_{fdr}-\sum_{twdr} NTC_{twdr}\, CTWD_{wdr} \\
&-\sum_{tkw} Invw_{tkw}\, CI_w-\sum_{tkd} Invd_{tkd}\, CID_d-\sum_{tkw} Z_{tkw} PN_{tk}-SP_{hpf}\, CSP \\
&-\sum X_{pv}\, LBH_j\, Clabor-\sum_{tkqfir} SC_{tkqfir}\, PC_{tki}\, PROB_{tkq} \\
&-\sum_{htkqwir} SW_{htkqwir}\, PC_{tki}\, PROB_{t-hkq}-\sum_{htkqdir} SD_{htkqdir}\, PC_{tki}\, PROB_{t-hkq} \\
&-\frac{1}{8}\sum_{tkqfir} SC_{tkqfir}\, PC_{tki}\, COL_{tkq}-\frac{1}{8}\sum_{htkqwir} SW_{htkqwir}\, PC_{tki}\, COL_{t-hkq} \\
&-\frac{1}{8}\sum_{htkqdir} SD_{htkqdir}\, PC_{tki}\, COL_{t-hkq}-\frac{1}{8}\sum_{htkqwr} SWO_{htkqwr}\, PN_{tk}\, COL_{t-hkq} \\
&-\frac{1}{8}\sum_{htkqwr} SWO_{htkqwr}\, PN_{tk}\, COL_{t-hkq}+\sum_{hj} PS_j\, QS_{hj} \qquad (2)
\end{aligned}
$$

The rest of the model is presented in Eqs. (3)–(21) and the appendix, which include all the required constraints of the model and the rest of the details. In the first constraint (3), the amount harvested (*QH*) is dependent on the plots harvested according to pattern v (Xpv), the expected production (*EH*) and the expected color distribution of the crops (*VQ*). In the second constraint (4), the salvaged crops (*QS*) depend on the amount harvested and the historical proportion of salvaged crops (*VS*). The amount harvested in (5) is also restricted by the available labor (*LAH* and *OP*), and the required labor for each box of crop j (*LRH*) and the harvest effort (*LBH*). The amount shipped to each packing facility is limited by the amount harvested (6). The production (*QP*) at the packaging plant in (7) is dependent on the pounds per crop required by each package and their estimated grade (*VG*), since the products are formed by the combination of the type of crop, grade and color. Production is limited by the capacity of the production line in (8). The quantity of crops to harvest in (9) by each pattern selected is limited to the amount of hectares in that plot (*AP*). There is also a maximum amount of day laborers available in (10).

Constraints:

$$QH_{hpq}=\sum_{v} X_{pv}\, EH_{hpv}\, VQ_{vjq} \quad \text{for every } h,\, p,\, q \qquad (3)$$

$$QS_{hj}=\sum_{v} X_{pv}\, EH_{hpv}\, VS_{hj} \quad \text{for every} \quad h,j \quad \text{where } j\in P(j) \qquad (4)$$

$$\sum_{p}(LRH_j\, QH_{hpq}+X_{pv}\, SH_{hv}\, LBH_j)\le LAH_h+OPl_h$$
$$\text{for every } h \quad \text{where } j\in P(j) \qquad (5)$$

$$\sum_{f}(SP_{hpqf})=QH_{hpq} \quad \text{for every } h,p,q \qquad (6)$$

$$QP_{hkqf}=\sum_{p} VG_{hpk}\cdot SP_{hpqf} \quad \text{where } k\in K(p) \quad \text{for each } h,p,q,f \qquad (7)$$

$$\sum_{k} QP_{hkqf}\le KP_f \quad \text{for every } h,f \qquad (8)$$

$$\sum_{v} X_{pv}=AP_p \quad \text{for every } p \qquad (9)$$

$$OPl_h\le MOP \quad \text{for every } h \qquad (10)$$

In (11) the quantity produced is transported from the packinghouse directly to customers (*SC*), to warehouses (*SPW*), or to *DCs* (*SPD*). The amount of products available at the warehouses depends on the sales of the past period and the arrivals (12), as explained before there could be contracted sales (*SW*) and open market sales (*SWO*) at the warehouses. The amount at hand at the *DC* at (13) also depends on the arrivals from the packinghouse (*SPD*) and the warehouse (*SWD*) and the sales (*SD*). The shelf life of the product is being considered by restricting the shipping decisions to those products that can withstand the time required for transportation (14). The contracted sales (*SW*, *SD*, and *SC*) are satisfied with products that are within the allowed shelf life based on the time of harvest (13). In addition, the open market sales do not need to comply with a specific volume requirement; however, they cannot surpass the maximum demand (*DM*) estimated for the market. It is also required for the delivery time of the open market sales to comply with shelf life constraints (15):

$$\sum_{fir} SC_{t_1 kqfir} + \sum_{tfwr} SPW_{ht_2 kqfwr} + \sum_{tfdr} SPD_{ht_3 kqfdr} = QP_{hkqf}$$
$$\text{for every } k,h,q,f \quad \text{where } t_1 = h + Ti_{fir},\ t_2 = h + TiPW_{fwr}$$
$$t_3 = h + TiPD_{fdr} \tag{11}$$

$$Invw_{htkqw} = Invw_{ht-1kqwr} + \sum_f SPW_{htkqfwr} - \sum_i SW_{ht_4 kqwir} - \sum_d SWD_{ht_5 kqwdr} + \sum_f SWO_{htkqw} + Z_{tkw}$$
$$\text{For all } \quad t \ge h,k,w,q \quad \text{where } t_4 = t + TiW_{wir}$$
$$t_5 = t + TiWD_{wdr} \tag{12}$$

$$Invd_{htkqd} = Invd_{ht-1kqdr} + \sum_f SPD_{htkqfdr} - \sum_i SD_{ht_6 kqdir} + \sum_w SWD_{htkqwdr}$$
$$\text{For all } \quad t \ge h,k,d,q \quad \text{where } \quad t_6 = t + TiD_{dir} \tag{13}$$

$$\sum_{fr} SC_{tkqfir} + \sum_{hwr} SW_{htkqwir} + \sum_{hdr} SD_{htkqdir} = DW_{tki} \quad \text{all} \quad t,k,i$$
$$\text{where } t - SL_{kq} \le h \le t \tag{14}$$

$$\sum_{hw} SWO_{htkqw} \le DM_{tk} \quad \text{all} \quad t,k \quad \text{where } t - SL_{kq} \le h \le t \tag{15}$$

Finally constraints (16)–(21) assure that the shipments sent between the facilities of the company and to the customers do not exceed the allowed capacity of the trucks in terms of weight and pallets of products:

$$\sum_k \text{Max}\left\{ \left\lceil \frac{RW_k\, SC_{tkfir}}{KTW} \right\rceil, \left\lceil \frac{RC_k\, SC_{tkfir}}{KTC} \right\rceil \right\} = NTI_{tfir}$$
$$\text{for every} \quad t,f,i,r \quad \text{where } k \in C(k) \tag{16}$$

$$\sum_k \text{Max}\left\{ \left\lceil \frac{RW_k\, SD_{htkqdir}}{KTW} \right\rceil, \left\lceil \frac{RC_k\, SD_{htkqdir}}{KTC} \right\rceil \right\} = NTD_{tdir}$$
$$\text{for every} \quad t,d,i,r \quad \text{where} \quad k \in C(k) \tag{17}$$

$$\sum_k \text{Max}\left\{ \left\lceil \frac{RW_k\, SW_{htkqwir}}{KTW} \right\rceil, \left\lceil \frac{RC_k\, SW_{htkqwir}}{KTC} \right\rceil \right\} = NTW_{twir}$$
$$\text{for every } t,w,i,r \quad \text{where } k \in C(k) \tag{18}$$

$$\sum_k \text{Max}\left\{ \left\lceil \frac{RW_k\, SPW_{htkqfwr}}{KTW} \right\rceil, \quad \left\lceil \frac{RC_k\, SPW_{htkqfwr}}{KTC} \right\rceil \right\} = NTP_{tfwr}$$
$$\text{for every } t,f,w,r \quad \text{where } k \in C(k) \tag{19}$$

$$\sum_k Max\left\{ \left\lceil \frac{RW_k\, SPD_{htkqfdr}}{KTW} \right\rceil, \left\lceil \frac{RC_k\, SPD_{htkqfdr}}{KTC} \right\rceil \right\} = NTK_{tfdr}$$
$$\text{for every } t,f,d,r \quad \text{where } k \in C(k) \tag{20}$$

$$\sum_k \text{Max}\left\{ \left\lceil \frac{RW_k\, SWD_{htkqwdr}}{KTW} \right\rceil, \left\lceil \frac{RC_k\, SWD_{htkqwdr}}{KTC} \right\rceil \right\} = NTC_{twdr}$$
$$\text{for every} \quad t,w,d,r \quad \text{where } k \in C(k) \tag{21}$$

4.1. Experiments for the operational model

The previous model is a Mixed Integer Problem (MIP), where most of the variables are continuous and only the variables that represent the number of shipments are integer. Just by looking at the shipment and transportation selection sub-problem, it is evident that it belongs to the "bin packing" type of problems, which are known to be NP Hard. Thus finding optimal solution of large instances of the problem is infeasible. This makes the selection of the number of shipments and the type of transportation mode (restrictions 16–21) the main issue when finding solutions for the model. Without these constraints, the current model converges fast to the optimal solution (see the last result in Table 3), for the problem instances of our experiment.

We now explore the structure of the operational model described by developing an experiment that changes some of the features of the model. For this experiment we selected the CPLEX® solver and its branch and bound algorithm as the solver. The results in Table 3 correspond to processing time (in seconds) for the different instances of the problem, which only change in the integer (*Int*) and binary (*Bin*) variables, and the integer number of containers to ship the crops (Trans Mode). The rest of the features of the problem are the number of crops (*J*), harvest periods (*TH*), customers (*I*), locations (*L*), plants (*P*), warehouses (*W*), distribution centers (*D*), products (*K*) and transportation modes (*H*), which were left the same. The rest of the fields in Table 3 include the use of cuts available in the solver (*Cut*) the absolute difference from optimality (*Abs*) and the time for reaching the solution (*Time*).

Through the results obtained from the different iterations of the algorithm, it was observed that the solver converges rather quickly to a level of optimality around 0.05%, so one way to reduce the time for larger instances is to relax the level of optimality. Another feature of the problem is that the integer containers in the transportation variables are the main complications of the problem instances. Given that the integer containers are relevant for the problem, since it might not be economically feasible to ship a fraction of the container, then other alternatives would be required for bigger instances. However, it is our appreciation that reducing the optimality gap in order to reduce the solving time might be a good compromise for this problem.

5. Case study

In order to test the validity of the proposed model in this section we apply it to the operational planning problem of a hypothetical fresh produce grower. We assume this producer grows tomatoes and bell peppers. As in the formulation of the model, we assume the planting and location decisions have already been made and are transmitted to the operational planning application (Table 4). The tactical plan displayed in Table 4 shows the crop selection (e.g. pepper crop 1), the timing of planting (week 1) and the area planted of each crop. According to this tactical plan, the growers planted 28 ha of bell peppers of crop 1 in the first week of production. Also relevant is the

Table 3
Problem size and running times of experiments.

J	TH	I	L	P	W	D	K	H	Row	Col	Non	Int	Bin	Tran mode	Cut	Abs (%)	Time
2	2	3	2	2	2	2	8	3	25,545	84,695	331,634	1608	7312	Y	N	0.30	3600
2	2	3	2	2	2	2	8	3	24,084	83,025	322,160	1608	9992	Y	N	0.46	95
2	2	3	2	2	2	2	8	3	24,084	83,025	322,160	1608	9992	Y	Y	0.49	33
2	2	3	2	2	2	2	8	3	25,545	84,695	331,634	0	7312	N	N	0.00	30

distribution of the planting effort, which called for most of planting to occur in the early periods of the planning horizon (weeks: 1–6) and complement in the last periods (16–17). For a more detailed explanation of the generation of the tactical plans and the crops involved the reader is referred to Ahumada and Villalobos (in press).

For these 3 weeks, the operational model uses the yield of the crops, which are provided by the tactical plan and the expected yield of crops. The model also relies on the estimate of the distribution of color at harvest, for the different harvesting patterns (Table 5), which were estimated based on Eq. (1).

The first column of Table 5 lists the frequency at which the crop is harvested (every day, every 2, 3, and 4 days), the second column lists the crop (in this case TOM corresponds to tomato), the next column shows the color at which the crop is harvested and the fourth column represents the fraction of harvest of a particular day that corresponds to a given color. For instance by harvesting every day in the 1st week of January, the expected distribution of harvest is 45% of tomatoes color 2, 34% of tomatoes color 3, 17% of color 4, and 4% of color 5.

The operational model considers fixed and variable costs of production and harvesting (see Table 6) for each crop and grade. The grades included for tomatoes is the smallest 5×6, or 60 tomatoes in a standard 25 pound box (*TOM* 5×6), others include 5×5, 4×5, and the largest tomatoes 4×4 (32 tomatoes in a 25 pound box). Similar industry grades are used for peppers (*SMA*, *MED*, *LGE*, and *XLGE*), which indicate diameters of each individual pepper of 2.2, 2.5, 3, and 3.3 in, respectively.

The fixed costs are those incurred for growing the crop and maintaining it. Harvest per box is the cost of labor required to harvest a box of each crop. Labor per box is the labor cost incurred for packing a box of each crop, and packing material is the cost of purchasing each box. We also used the daily prices of crops for the 3 weeks, which were obtained from the USDA database (USDA, 2007).

Variable costs include those required to harvest, pack and transport products to the final customer, which are not incurred if prices for products are below these costs and the products are discarded, which is not a feasible option in the cases that the grower has to meet contractual commitments. The operational model can accommodate both situations, spot and contract market, by using restrictions for minimum and maximum demands. As mentioned before in this model there are two types of customers, the first ones are those that buy *FOB* on the warehouses, which usually have no committed price or volume and buy at the open market price. The second is formed by customers who have a closer relationship and/or have a commitment of volume that the grower is required to satisfy. For this second type of consumer, the assumption is that the grower

Table 4
Tactical plan and expected yield.

Week planted	Pepper crop 1	Tomato crop 1	Tomato crop 2	Week total
Program of crops (ha)				
1	28	–	–	28
3	–	114	–	114
4	–	20	–	20
6	–	–	29	29
7	22	–	24	46
11	–	85	–	85
12	23	–	–	23
13	–	47	–	47
16	20	–	–	20
18	–	89	–	89
Planted total	93	354	152	500

Table 5
Distribution of color for the 3 weeks.

First week of January				Third week of February				Third week of March			
Days	**Crop**	**Color**	**Fraction**	**Days**	**Crop**	**Color**	**Fraction**	**Days**	**Crop**	**Color**	**Fraction**
1	TOM	2	0.45	1	TOM	2	0.44	1	TOM	2	0.43
1	TOM	3	0.34	1	TOM	3	0.34	1	TOM	3	0.35
1	TOM	4	0.17	1	TOM	4	0.18	1	TOM	4	0.18
1	TOM	5	0.04	1	TOM	5	0.05	1	TOM	5	0.04
2	TOM	2	0.34	2	TOM	2	0.32	2	TOM	2	0.30
2	TOM	3	0.36	2	TOM	3	0.35	2	TOM	3	0.35
2	TOM	4	0.23	2	TOM	4	0.25	2	TOM	4	0.27
2	TOM	5	0.06	2	TOM	5	0.07	2	TOM	5	0.08
3	TOM	2	0.24	3	TOM	2	0.22	3	TOM	2	0.19
3	TOM	3	0.34	3	TOM	3	0.32	3	TOM	3	0.30
3	TOM	4	0.32	3	TOM	4	0.34	3	TOM	4	0.36
3	TOM	5	0.10	3	TOM	5	0.12	3	TOM	5	0.15
4	TOM	2	0.16	4	TOM	2	0.14	4	TOM	2	0.11
4	TOM	3	0.28	4	TOM	3	0.26	4	TOM	3	0.23
4	TOM	4	0.38	4	TOM	4	0.39	4	TOM	4	0.40
4	TOM	5	0.17	4	TOM	5	0.21	4	TOM	5	0.25

Table 6
Fixed and variable costs and parameters.

Product and grade	Fixed × box	Harvest × box	Weight × box	Boxes × pallet	Boxes × hour	Labor × box	Packing material
TOM 5 × 6	3.26	0.20	21	88	30	0.44	0.88
TOM 5 × 5	3.26	0.20	22	88	30	0.44	0.88
TOM 4 × 5	3.26	0.20	23	88	30	0.44	0.88
TOM 4 × 4	3.26	0.20	23	88	30	0.44	0.88
PEP SMA	3.78	0.24	25	56	30	0.46	0.93
PEP MED	3.78	0.24	25	56	30	0.46	0.93
PEP LGE	3.78	0.24	25	56	30	0.46	0.93
PEP XLGE	3.78	0.24	25	56	30	0.46	0.93

handles the delivery and storage up to their final location. The selected weeks have different harvesting requirements given that there are multiple types of crops planted at different times along the planning season. Table 7 presents the hectares for each one of the plots to harvest in each week, along with the expected amount of boxes to harvest per hectare. This table also includes the labor available for each one of these weeks, both for fixed and day laborers.

The harvest plan for the first 2 weeks (days 1–12) of January can be shown in Table 8, where the first part of the table presents a harvest plan that includes service restrictions, such as the longest lead-time to the final customer, the labor and shelf life constraints. The results from the model suggest harvesting tomato every 3 days and peppers every 4 days, which is consistent with the current practice of growers for that time of the year. If on the other hand the penalization for color maturity is included in the model then the harvest frequency changes to the results presented in the second-half of Table 8. As it can be observed the frequency of harvest is increased from 2 to 3 times per week, resulting in more hectares harvested per day. Finally, if instead of using rejection probabilities and color maturity we relaxed the service and transportation constraints (transforming containers to continuous variables), then the recommended policy would be to harvest both crops every 4 days, since this practice would save labor costs (those results are not shown in Table 8).

The different alternatives provided by the model, suggest that it is possible to determine the trade-off between the lack of freshness at the consumer end with the added labor and transportation cost at the grower's side.

We expect different results for the case of the third week of February (Table 9), since prices are at their lowest level because of the peak in the production of growers. As it can be observed in Table 9, harvest frequency is reduced on this week, even with higher environmental temperatures that would increase the rate of maturity of the fruits. One reason for this behavior is that according to the tactical plan that week in February is the one with the peak requirement of labor, thus there is a limited amount of day laborers available.

A different scenario is presented on the week in March, which has better prices and the looser labor constraints than the week in February. As expected, those changes are accounted in the results from Table 10. In this week the frequency of harvest is higher than in previous weeks given that the temperatures are also higher and there is more temporary labor available for harvesting the crops.

The results obtained from the operational model for the 3 weeks presented suggest that the model proposed is responsive to the changes in the environment and to the limitations of labor and the market. This type of model is one of the first of its kind that uses biological functions with mixed integer programs to determine the best harvesting and distribution policies for a short period of time. Moreover, the proposed model can be used to improve current labor management policies, which are currently based in fixed policies to a dynamic planning of harvest and distribution decisions, based on the information available.

Table 7
Production estimates for plots in the weeks selected.

	Crop	**Plot**	**Hectare**	**Boxes × hectare**	**Labor**	**Day labor**
First week of January	Tomato	T1	134	301	515	100
	Tomato	T2	53	309		
	Pepper	C1	28	546		
Third week of February	Tomato	T1	134	682	537	148
	Tomato	T2	53	632		
	Tomato	T3	85	670		
	Tomato	T4	47	496		
	Pepper	C2	22	632		
Third week of March	Tomato	T3	85	227	466	200
	Tomato	T4	47	332		
	Tomato	T5	89	500		
	Pepper	C3	23	655		

Table 8
Results for 1st week in January.

Plot	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
T1	30	0	0	30	0	0	30	0	0	30	0	0
T1	0	47	0	0	47	0	0	47	0	0	47	0
T1	0	0	57	0	0	57	0	0	57	0	0	57
T2	28	0	0	28	0	0	28	0	0	28	0	0
T2	0	24	0	0	24	0	0	24	0	0	24	0
C1	15	0	0	0	15	0	0	0	15	0	0	0
C1	0	13	0	0	0	13	0	0	0	13	0	0
Total	73	84	57	59	86	70	59	71	72	72	71	57
Using color penalizing function												
T1	63	0	63	0	63	0	63	0	63	0	63	0
T1	0	71	0	71	0	71	0	71	0	71	0	71
C1	16	0	0	0	16	0	0	0	16	0	0	0
C1	0	12	0	0	0	12	0	0	0	12	0	0
T2	0	8	0	8	0	8	0	8	0	8	0	8
T2	3	0	0	3	0	0	3	0	0	3	0	0
T2	0	12	0	0	12	0	0	12	0	0	12	0
T2	0	0	12	0	0	12	0	0	12	0	0	12
T2	0	0	15	0	0	0	15	0	0	0	15	0
T2	0	0	0	3	0	0	0	3	0	0	0	3
Total	83	102	75	82	91	102	67	91	91	94	75	91

Table 9
Results for 3rd week in February.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
T1	8	0	0	8	0	0	8	0	0	8	0	0
T1	0	21	0	0	21	0	0	21	0	0	21	0
T1	0	0	35	0	0	35	0	0	35	0	0	35
T1	0	0	23	0	0	0	23	0	0	0	23	0
T1	0	0	0	26	0	0	0	26	0	0	0	26
T2	16	0	0	0	16	0	0	0	16	0	0	0
T2	0	37	0	0	0	37	0	0	0	37	0	0
T3	21	0	21	0	21	0	21	0	21	0	21	0
T3	0	6	0	6	0	6	0	6	0	6	0	6
T3	32	0	0	32	0	0	32	0	0	32	0	0
T3	0	19	0	0	19	0	0	19	0	0	19	0
T3	0	0	6	0	0	6	0	0	6	0	0	6
C2	0	0	21	0	0	0	21	0	0	0	21	0
T4	6	0	0	0	6	0	0	0	6	0	0	0
T4	0	32	0	0	0	32	0	0	0	32	0	0
Total	83	116	107	73	83	117	106	73	84	116	105	74

Table 10
Results for 3rd week in March.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
T3	36	0	36	0	36	0	36	0	36	0	36	0
T3	0	49	0	49	0	49	0	49	0	49	0	49
T4	38	0	38	0	38	0	38	0	38	0	38	0
T4	0	9	0	9	0	9	0	9	0	9	0	9
C3	0	23	0	0	0	23	0	0	0	23	0	0
T5	47	0	47	0	47	0	47	0	47	0	47	0
T5	0	42	0	42	0	42	0	42	0	42	0	42
Total	121	123	121	100	121	123	121	100	121	123	121	100

Therefore the use of the proposed modeling tool would be very useful for maximizing the revenue of growers under different climate and markets. Furthermore, by taking into account the perishable nature of crops and different alternatives for distributing them, the model could be used to determine the profitability of potential customers and for analyzing new markets.

6. Conclusions and future research

This paper presented an operational model designed for providing decisions for harvesting, packing and distribution of crops with the objective of maximizing the revenues of the grower of perishable agricultural products. The model deals with labor availability, price dynamics, and the variable effects of the weather and plant biology through different functions and approximations. The main benefit of this research is that it provides a model that can assist the grower to make decisions in the midst of complex changing environments.

The use of the proposed modeling tool would be very useful for maximizing the revenue of growers under different climate and dynamic markets. By taking into account the perishable nature of crops and different alternatives for distributing them, the model could be easily extended to determine the profitability of potential customers and for analyzing new markets.

One advantage of the proposed MIP model is that realistic instances of operational planning problems can be solved with commercially available solvers. Thus, the current application can serve as the first step for further developments in this area, since it addresses many of the basic requirements in the short term planning for fresh produce.

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Appendix

Indices

$t \in T$ planning periods (days)
$h \in TH(j,l) \subseteq \mathbf{T}$ set of feasible harvesting days for crop j in location l
$p \in P$ plot formed by the area in location l planted with crop j
$j \in J$ different crops
$k \in K(j)$ products of crop j (package, grade)
$C(k)$ compatible products for storage and transportation in the same container
$w \in W$ warehouses available for storage
$i \in I$ customers
$d \in D$ distribution centers
$f \in PF$ packaging facilities
$r \in TM$ transportation mode
$q \in Q$ quality of products (color)
$v \in V(j)$ harvesting patterns for crop j

Parameters

AP_p total area planted in plot p (ha)
EH_{hpv} expected harvest at period h of plot p harvested by pattern v (boxes).
SH_{hv} if pattern v is requires to harvest in period h
VQ_{vjq} percentage of crop j with quality q in by pattern v
VG_{hpk} percentage of product k from plot p at period h
VS_{hj} percentage of the crop j that is salvaged at period h (fraction)
LAH_h labor available for harvesting in period h (h)
LRH_j boxes of crop j harvested per hour
LBH_j labor hours required to cover one hectare of crop j
SL_{kq} shelf life of product k with quality q
KTC capacity of container in pallets
KTW capacity of container in weight
KP_f capacity of plant f (boxes per period)
DW_{tki} expected demand from customer i of product k in time t
DM_{tk} expected demand (open market) of product k in period t
Ti_{fir} time from packing facility f to customer i by transportation mode r
TiW_{wir} time from warehouse w to customer i by transportation mode r
TiD_{dir} time from DC d to customer i by transportation mode r
$TiPW_{fwr}$ time from packing facility f to warehouse w by transportation mode r
$TiPD_{fdr}$ time from packing facility f to DC d by transportation mode r
$TiWD_{wdr}$ time from warehouse w to DC d by transportation mode r
RW_k amount of crop weight per box of product k
RC_k number of boxes of product k in a pallet
COL_{t-hkq} expected color product k with initial color q after n days of harvest ($n=t-h$)
MOP extra men-hours available from day laborers
$PROB_{t-hkq}$ estimate of the probability that the product with color q is not accepted by customers based in the time elapsed ($n=t-h$)

Cost parameters

PN_{tk} price per product k on period t in the open market
PC_{tki} price per product k on period t sold to customer i
PS_j salvage price of crop j
CF_j fixed cost per box of crop j
CH_j cost of harvesting a box of crop j
CK_k cost of packing a box of product k
CI_w cost of inventory at warehouse w per pallet of product (pallet/day)
CID_d cost of inventory at DC d per pallet of product (pallet/day)
Ct_{FIR} cost of transportation from facility f to customer i by mode r
CTW_{wir} cost of transportation from warehouse w to customer i by mode r
CTD_{dir} cost of transportation from DC d to customer i by mode r
$CTPW_{fwr}$ cost from packing facility f to warehouse w by mode r
$CTPD_{fdr}$ cost of transportation from facility f to DC d by mode r
$CTWD_{wdr}$ cost of transportation from warehouse w to DC d by mode r
$Clabor$ cost of an hour of labor at the field

Decisions variables

X_{pv} area of plot p harvested using pattern v
QH_{hpq} harvest (boxes) of quality q from plot p in period h
SP_{hpqf} quantity of crop with quality q to ship from plot p to facility f in period h
QS_{hj} quantity salvaged of crop j in harvesting period h
QP_{hkqf} quantity of product k with quality q packed at facility f in period h
SC_{tkqfir} product k of quality q shipped from facility f to customer i in period t by mode r

$SPD_{htkqfdr}$ product k of quality q harvested at h shipped from facility f to DC d in period t by mode r

$SPW_{htkqfwr}$ product k of quality q harvested at h shipped from facility f to warehouse w in period t by mode r

$SD_{htkqdir}$ product k of quality q harvested at h shipped from DC d to customer i in period t by mode r

$SWD_{htkqwdr}$ product k of quality q harvested at h shipped from warehouse w to DC d in period t by mode r

$SW_{htkqwir}$ product k of quality q harvested at h shipped from warehouse w to customer i in period t by mode r

SWO_{htkqw} product k with quality q harvested at h sold from warehouse w in period t

$Invw_{htkqw}$ inventory of product k at period t with quality q in warehouse w harvested at h

$Invd_{htkqd}$ inventory of product k at period t with quality q in DC d harvested at h

Z_{tkw} quantity to purchase of product k, in period t for warehouse w

Opl_h operator hours hired in the field at time h

NTI_{tfir} number of containers sent to customer i from facility f in period t by mode r

NTD_{tdir} number of containers sent to customer i from DC d in period t by mode r

NTW_{twir} number of containers to customer i from warehouse w in period t by mode r

NTP_{tfwr} number of trucks sent from facility f to warehouse w in period t by mode r

NTK_{tfdr} number of containers sent to DC d from facility f in time t by mode r

NTC_{twdr} number of containers sent to DC d from warehouse w in time t by mode r

where X_{pv}, QH_{pq}, SP_{hpqf}, QP_{hkqf}, SC_{tkqfir}, $SPD_{htkqfdr}$, $SW_{htkqwir}$, $SPW_{htkqfwr}$, $SWD_{htkqwdr}$, $SD_{htkqdir}$, $SWO_{htqkwir}$, $Invw_{htkqw}$, $Invd_{htkqd}$, Z_{tkw}, $Opl_h \in R^+$ and $NTIfrir$, $NTDtdir$, $NTWtwir$, $NTPtfwr$, $NTKtfdr$, $NTCtwdr \in Z^+$

References

Ahumada, Omar, 2008. Models for Planning the Supply Chain of Agricultural Perishable Products, Ph.D. Dissertation, Arizona State University.

Ahumada, Omar, Villalobos, J.Rene, 2009. Application of planning models in the agri-food supply chain: a review. European Journal of Operational Research 195, 1–20.

Ahumada, Omar, Villalobos, J. Rene, in press. Planning the production and distribution of fresh produce. Annals of Operations Research. doi:10.1007/s10479-009-0614-4.

Allen, Stuart J., Schuster, Edmund W., 2004. Controlling the risk for an agricultural harvest. Manufacturing and Service Operations Management 6 (3), 225–236.

Calvin, Linda, Cook, Roberta, 2001. US Fresh Fruit and Vegetable Marketing: Emerging Trade Practices, Trends, and Issues. Agricultural Economic Report 795. United States Department of Agriculture.

Ferrer, Juan C., MacCawley, Alejandro, Maturana, Sergio, Toloza, Sergio, Vera, Jorge, 2007. An optimization approach for scheduling wine grape harvest operations. International Journal of Production Economics 112 (2), 985–999.

Gary, Christian, Tchamitchian, Marc, 2001. Modelling and management of fruit production: the case of tomatoes. In: Tijskens, L.M.M., Hertog, Maarten L.A.T.M., Nicolai, Bart M. (Eds.), Food Process Modeling. Woodhead Publishing, Cambridge, pp. 201–229.

Hertog, Maarten L.A.T.M., Lammertyn, Jeroen, Desmet, Michele, Scheerlinck, Nico, Nicolai, Bart M., 2004. The impact of biological variation on postharvest behavior of tomato fruit. Posthaverst Biology and Technology 34, 271–284.

Heuvelink, E.P., 1996. Dry matter partitioning in tomato: validation of a Dynamic Simulation Model. Annals of Botany 77, 71–80.

Johnson, Demcey, Krissof, Barry, Young, Edwin, Hoffman, Linwood, Lucier, Gary, Breneman, Vince, 2006. Eliminating Fruit and Vegetable Planting Restrictions: How Would Markets be Affected? Economic Research Service ERR-30. USDA.

Jones, James W., Dayan, Ehud, Allen, L.H., van Keulen, Herman, Challa, Hugo, 1991. Dynamic tomato growth and yield model (TOMGRO). Transactions of the ASAE 34 (2), 663–672.

Jones, Phillip C., Kegler, Greg, Lowe, Timothy J., Traub, Rodney D., 2003. Managing the seed-corn supply chain at syngenta. Interfaces 33 (1), 80–90.

Lopez-Cruz, Irineo L., Ramirez-Arias, Armando, Rojano-Aguilar, Abraham, 2005. Modelos matemáticos de hortalizas en invernadero: Trascendiendo la contemplación de la dinámica de los cultivos. Revista Chapingo, Serie Horticultura 11, 25–267.

Marcelis, Leo F.M., 2001. Yield and Quality prediction of vegetables: the case of cucumbers. In: Tijskens, L.M.M., Hertog, Maarten L.A.T.M., Nicolai, Bart M. (Eds.), Food Process Modeling. Woodhead Publishing, Cambridge.

McNeal, Brian L., Scholberg, Johannes M.S., Jones, James W., Stanley, Craig D., Csizinsky, Alexander A., Tom, Obreza A., 1995. Application of a tomato-growth model (TOMGRO) to field-grown tomato. Soil and Crop Science Society of Florida Proceedings 54, 86–93.

Miller, W.A., Leung, L.C., Azhar, T.M., Sargent, S., 1997. Fuzzy production planning model for fresh tomato packing. International Journal of Production Economics 53, 227–238.

Rantala, Juho, 2004. Optimizing the supply chain strategy of a multi-unit finish nursery. Silva Fennica 38 (2), 203–215.

Rong, A., Akkerman, R., Grunow, M., 2011. An optimization approach for managing fresh food quality throughout the supply chain. International Journal of Production Economics 131 (1), 421–429.

Saltveit, Mikal E., 2005. Fruit ripening and fruit quality. In: Heuvelink, E.P. (Ed.), Tomatoes. CABI Publishing, Wallingford, Oxfordshire, UK, pp. 145–168.

Schouten, Rob E., Huijben, Tanja P.M., Tijskens, L.M.M., van Kooten, Olaf, 2007a. Modelling quality attributes of truss tomatoes: linking colour and firmness maturity. Postharvest Biology and Technology 45, 298–306.

Schouten, Rob E., Huijben., Tanja P.M., Tijskens, L.M.M., van Kooten, Olaf, 2007b. Modelling the acceptance period of truss tomato batches. Postharvest Biology and Technology 45, 307–316.

Thysen, I., 2000. Agriculture in the Information Society. Journal of Agricultural Engineering Research 76 (3), 297–303.

Tijskens, L.M.M., Polderdijk, Janna J., 1996. A generic model for keeping quality of vegetable produce during storage and distribution. Agricultural Systems 51 (4), 431–452.

Tijskens, L.M.M., Evelo, R.G., 1994. Modelling colour of tomatoes during postharvest storage. Postharvest Biology and Technology 4, 85–98.

USDA, 1997. United States Standards for Grades of Fresh Tomatoes. Available from: 〈http://www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5050331〉.

USDA, 2007. Custom Report. US Department of Agriculture. Available from: 〈http://marketnews.usda.gov/portal/fv〉 (accessed 15.10.07).

Zhang, W., Wilhelm, W., 2009. OR/MS decision support models for the specialty crops industry: a literature review. Annals of Operations Research. doi:10.1007/s10479-009-0626-0.