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A tactical model for planning the production and distribution of fresh produce

Omar Ahumada · J. Rene Villalobos

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Abstract We present an integrated tactical planning model for the production and distribution of fresh produce. The main objective of the model is to maximize the revenues of a producer that has some control over the logistics decisions associated with the distribution of the crop. The model is used for making planning decisions for a large fresh produce grower in Northwestern Mexico. The decisions obtained are based on traditional factors such as price estimation and resource availability, but also on factors that are usually neglected in traditional planning models such as price dynamics, product decay, transportation and inventory costs. The model considers the perishability of the crops in two different ways, as a loss function in its objective function, and as a constraint for the storage of products. The paper presents a mixed integer programming model used to implement the problem as wells as the computational results obtained from it.

Keywords Production and distribution planning · Perishable products · Linear programming

1 Introduction

In recent years, a renewed interest on the application of advanced planning tools for fresh agricultural supply chains has emerged. However, adapting existing planning techniques to fresh agricultural supply chains is a task whose complexity is compounded by the perishable nature of these products. Among the critical issues in the planning of growing perishable products we can mention the long supply lead times, the short shelf lives, as well as significant supply and demand uncertainties (Lowe and Preckel 2004). These peculiarities call for planning models that incorporate decisions regarding harvesting, market access, method-of-sale, logistics, vertical coordination, and risk management (Epperson and Estes 1999). In this paper we present an integrated modeling approach for the tactical planning of the production and distribution of perishable agricultural products. Tactical decisions include those

O. Ahumada · J.R. Villalobos (✉)
Department of Industrial Engineering, Arizona State University, Tempe, AZ 85287-5906, USA
e-mail: Rene.villalobos@asu.edu

that have to be made at the beginning of the season such as what to sow, when to sow it, and what potential markets to target. In particular, in this paper we are concerned with the planning problem for an individual grower of fresh produce who would like to maximize his revenues and avert the risks associated with an uncertain market. Some of the factors to consider are the crops' prices, demand, yields and labor availability. The model to be presented handles decisions such as detailed planting plans, labor requirements, rough estimates of distribution planning, harvesting and growing policies.

The underlying motivation of the work to be presented is to assist the producers in the increasingly complex and competitive fresh agricultural industry. This industry requires large investments in technology, facilities and labor; while being subjected to highly variable crop yields and market prices, thus making planning tools, like the ones we present in this research, a necessity for the long term survival and profitability within this industry. The paper applies the proposed model to the case of the Mexican export-oriented fresh produce industry. This particular application deals with the emerging requirements of the fresh produce industry, such as contracted production and more distribution activities.

In the reminder of this paper we first present a review of the literature (Sect. 2); the description and development of the tactical model in Sect. 3; the case study of export oriented Mexican growers in Sect. 4; and, finally, in Sect. 5 we present our conclusions and plans for future research.

2 Literature review

Traditionally, agricultural planning models have incorporated a variety of decisions, such as crop planning, machine scheduling and harvest planning, among many others (Glen 1987; Lowe and Preckel 2004). The majority of existing planning models has focused on traditional crops, with a limited number of them focusing on highly perishable products such as fresh produce. However, the rate of development for highly perishable crops has been increasing in recent years; especially for the planning of high value crops, such as flowers and horticultural products that require large investments in technology and labor (Ahumada and Villalobos 2009). In this section, we present some of the most relevant contributions in the area of tactical planning of perishable crops, including crop planting, harvesting and transportation planning. From the large number of papers available, we focus mainly on those models that have been successfully implemented.

From the perspective of tactical planning, Van Berlo (1993) developed a goal programming model to plan and coordinate the production and supply of raw materials from the field to a processing plant, in a vertically integrated vegetable processing industry with final products in the form of cans of peas. A related contribution is the work of Hamer (1994) who developed a model that allowed the simultaneous selection of different varieties of Brussels' sprouts and the planting and scheduling decisions to assure a steady supply of quality and size of Brussels sprouts demanded from the customers over the planning horizon.

More recently, other applications of tactical planning have emerged, such as the work by Caixeta-Filho et al. (2002). These authors use an LP model for planning the production of flowers in a Brazilian greenhouse. The main decision variable is the number of flowers to produce in each specific greenhouse at a particular time period. Some of the constraints of the model include the amount to harvest and plant for each period. The objective of the model is to satisfy the demand of customers while maximizing revenue. The reported benefits of using this model are additional sales and profits, with an estimated 32% increase in the farmers' profit margin.

Other models handle only parts of the tactical plan, such as harvesting or transportation. An example of this type of model is given by the work of Allen and Schuster (2004), who developed a model for calculating the capacity and rate of harvest required for grape production. The objective of the model is to minimize the losses in crops, caused by weather, and to minimize overinvestment costs resulting from installing excess capacity. A major contribution of the paper is the use of nonlinear programming to reduce the risk of uncertain weather. The benefits reported from the use of this model include \$2 million in capital avoidance from reduced investment on harvesting equipment and improved risk assessment for the incorporation of new crop areas. A second application in grape harvesting is given by the work of Ferrer et al. (2008) who developed an MIP model for optimally scheduling the harvesting operations of wine grapes with the objective of reducing total costs. The model considers the costs of harvesting activities and the loss of quality of the grapes for delaying harvesting. The decisions in the model include the amount of grapes to harvest from the different plots in each period, the routing of harvesting among plots and the number of workers to hire or lay off for each period of the harvesting season. The authors estimated the benefits of the use of the model at a 27% decrease in operational cost and a 16% reduction in labor costs.

Two recent contributions in the area of transportation planning for perishable crops include the works by Faulin (2003) and Osvald and Stirn (2008). Faulin describes the implementation of an algorithm for planning the routes of a company handling frozen vegetables. The objective is to improve the efficiency metrics of the fleet and reduce the costs incurred. One drawback of this model is that it did not consider the perishable nature of the products being transported. In contrast the work of Osvald and Stirn considers the perishable nature of the products by using a linear loss function that is dependent on the time spent during transportation. The objective of the model is to minimize the distribution costs, through the costs of vehicles, total distance traveled and the loss of quality of the products. The authors estimate that there are significant reductions in overall costs (27% or more) by using their model.

From the review of the available literature, we are able to draw the conclusion that there are no models that consider production and distribution decisions in an integrated way. Another finding is that there are considerable benefits from applying advanced planning techniques to the supply chain of fresh agricultural products. The benefits reported in the literature include an increase in profit margins, reductions in operational costs and better planning of activities at the tactical and operational level. Given the size and recent consolidation of the fresh produce industry, if only a small fraction of the reported benefits are realized, this would more than cover any effort or investment required to develop, run and maintain the decision tools needed for the planning of perishable products.

In the next section we present a general model that meets the particular needs of fresh agricultural producers. One of the contributions of the model presented here is that it integrates planting, harvesting and distribution decisions into a single tactical model. Traditionally, these decisions have been addressed individually. A second contribution is the inclusion of the perishable nature of fresh produce in the model.

3 Tactical planning model

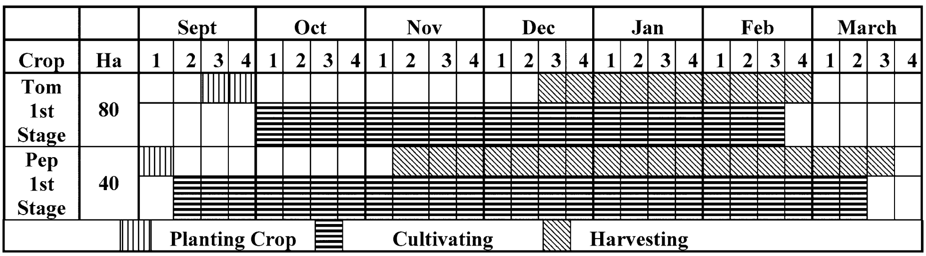
In the fresh produce industry, vertically integrated producers are called grower/shippers and they form an increasingly important component of the supply chain of fresh horticultural products. Grower/shippers face changing market conditions due to the consolidation of supermarket chains and the new purchasing policies implemented by those chains (Dimitri et al. 2003). Furthermore, it is expected that the consolidation of supermarket chains will continue, or even increase, in the near future, resulting in large customers who will demand a closer relationship with growers and year round supply of fresh produce (Kaufman et al. 2000). The producers that have the possibility of efficiently accessing directly the final market (grower-shippers) can benefit from the planning tools presented in this paper since they must design and coordinate their supply chain to meet the new realities of the market. In fact, we believe that only those growers/shippers with access to the appropriate advanced planning tools will be effective players in the new fresh supply chain.

3.1 Planning activities and labor requirements

As an example of the type of seasonal planning problems in the industry, we provide the following description of the planning environment surrounding Mexican open-field growers, who produce a significant portion of the fresh tomatoes and peppers consumed in the US market. These growers and their practices are representative of the horticultural industry in North America. Commonly, fresh produce growers make several decisions regarding production and planting. Planting decisions include the selection of the best variety, the selection of the total area to plant of each variety and when to plant the selected varieties. These decisions are, for the most part, made based on forecasts of the demand and prices expected in the season ahead. The effects of planting decisions affect the growing season, which ranges between 6–12 months, depending on the particular strategy of the producer (Thompson and Wilson 1997).

As an example of a typical plan, in Table 1 we present a list of activities represented on weekly buckets. The major activities in the production plan (Table 1) start with the planting of crops immediately followed by cultivation, and later, by harvesting activities. In Table 1 it can also be observed that the harvesting plan can last several weeks. From the planning program depicted in Table 1 it can also be observed that during the growing season, the cultivating and harvesting activities overlap significantly. One of the implications of this overlap is that these two activities use a commonly scarce resource, i.e., manual labor. This implies the need for growers to plan and coordinate their labor to handle peak labor requirements. The main issue with labor planning is that seasonal agricultural labor is in short supply, and given the large requirements of fresh produce production, labor can become the most restrictive resource for planning. For this reason, our model accounts for the availability of seasonal and temporary labor. The difference among these two is that seasonal laborers are under contract for the entire or most of the season. Hiring seasonal laborers requires a certain minimum amount of work per week, since if the work falls below the agreed upon minimum, laborers are paid a predetermined minimal wage. On the other hand, temporary laborers can be hired weekly or daily as needs arise, but at a premium. The number of both

Table 1 Typical program for growing tomatoes and bell peppers in hectares (ha)



types of laborers is restricted by the supply of seasonal laborers and by the competition from other growers for the scarce labor.

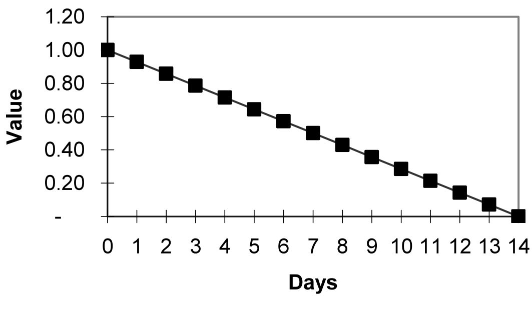
For the case study to be presented in this paper, labor requirement data was obtained from interviews with growers with operations in North America. From the data gathered, we found out that there are similarities in the labor requirements for planting and cultivation of tomatoes and peppers. But the labor demands from these crops differ significantly at the time of harvest, for which tomatoes usually require twice the number of workers than peppers. An expected benefit of the proposed model is that the decisions regarding crops and labor are planned in an integrated way, instead of planning the planting crops first and then labor requirements, which is common practice in the industry.

3.2 Handling the planning of perishable crops

One of the main differences between traditional agricultural models and the model we propose, is the management of perishability. Our model handles the decay of fresh products in two different ways. First, by limiting the maximum storage time allowed, which is crop dependent (shelf life), and by incorporating metrics that can be used as surrogates for freshness of the product throughout its traversal of the supply chain. For example, in the case of tomatoes, the color of the fruit can be used to determine the freshness.

Invoking constraints that limit shelf life serves to comply with any proposed production-distribution plan according to the acceptable characteristics of the crop. However, these constraints do not encourage the freshness of the products, since as long as products are within the specifications, the model does not penalize for delivering close to the expiration date. This could lead to some odd decisions, such as preferring the use of railroad over trucks for highly perishable items, since railroads usually offer a lower transportation cost. To avoid these problems, the objective function is modified to include the cost of inventory lost while being transported, which can be modeled using a decay function (Nahmias 1982; Raafat 1991). This function represents the physical decay of the products, or opportunity cost, for shelf life reduction, if we assume the price received by the growers is dependent on the quality and freshness of the products (Goyal and Giri 2001). To model the decay in the products, a linear function is proposed to reduce the value of the products according to the length of transportation time; this function is similar to that proposed by Osvald and Stirn (2008). Figure 1 shows the decay function used for peppers, which decreases the value of the product at a constant rate over time until the shelf life of the product is reached. A similar decay function is used for tomatoes (e.g. shorter shelf life). Such a function was previously suggested for the case of fresh produce (Fujiwara and Perera 1993), and for Yoghurt production (Lutke Entrup et al. 2005).

Fig. 1 Loss function for peppers



The model to be presented in this paper will incorporate into the planning process both types of perishability considerations just presented; i.e., restrictions of maximum elapsed time between the harvest and reception of the products by the buyer, and the loss of value of the products by delaying their delivery to the customer.

3.3 Formulation of the model

Producers of fresh agricultural products have different needs according to the particular characteristics of their business. The integration of the grower in the value chain is one of the main drivers of the coordination between production and distribution. In this regard, some producers leave the marketing and distribution of their products to brokers and other intermediaries, while other producers market and distribute their own products to obtain a larger share of the total value chain. Figure 2 presents a simplified schematic of the different transactions in the fresh-produce supply chain as seen by a grower/shipper.

According to this schematic, grower-shippers may have several locations for planting their crops (L1–L3). These locations could be significantly different from each other in terms of their geographical position or existing infrastructure such as greenhouses and other protected agricultural facilities. Growers can also have one or more packing facilities to process their crops (P1, P2), warehousing facilities to store the crops (W1, W2) and distribution centers (D1, D3) to deliver products to customers (C1–C3). In this context, the purpose of the formulation to be presented is to provide a basic model that can be easily adaptable to the needs of the different fresh agricultural producers.

In this paper we assume that the distribution of demand, yield and market prices can be represented by their respective expected values. We also assume that the basic infrastructure (land, warehouse facilities, etc.) is already in place and its capacity has already been set; thus, we assume that strategic decisions have already been made and we focus only on tactical level planning. Consequently, we assume that the growing locations (L1–L3) and their production characteristics are already defined. However, the total amount to plant in each location is a tactical decision variable limited by the maximum amount of land available.

The main decisions in the tactical model involve when and how much to plant of each crop, when to harvest and sell the crops, the labor resources to contract and the transportation mode to use to deliver the product to the different customers. For each one of the customers we assume that the total amount of product to deliver exceeds a certain minimum, which varies, depending on the supply contracts between the growers and their customers. Other decisions include the storage of products for later use and the selection of facilities from which to ship the products. In addition, the model selects the best transportation mode based on costs, the loss of quality during transit, the maximum delivery time allowed by the customer and other service requirements. For these transportation decisions we assume, since transportation is usually hired from third-party providers, unlimited transportation capacity.

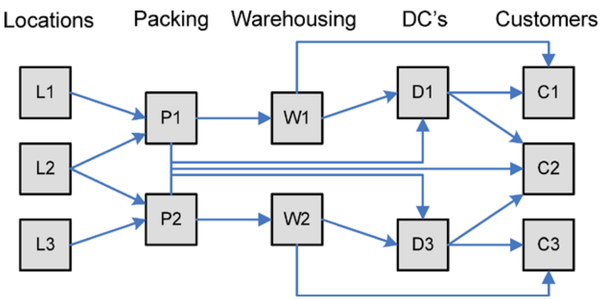


Fig. 2 Grower-shippers' transactions

The objective of the model is to maximize the expected revenue for the grower. This revenue is given by the combination of external conditions, which are out of the farmer's control, such as expected market prices, and those determined by the farmer himself, such as when, what and how much to plant and harvest in a given season. For this model all planning periods (t) are assumed to be finite, discrete, and defined in multiples of weeks (see Appendix A). The periods in which planting is feasible are represented by the subset **TP**, and those periods in which it is feasible to harvest are represented by the subset **TH**. A particular product (k) is formed by the combination of the crop included, the size of the fruits and the quality of the crop; this implies that for any given crop there could be multiple products. For instance, the crop "tomato" can be segregated into different qualities and sizes that correspond to different products. Other discrete sets represent the options available for transportation modes (r), packing facilities (f), customers (i), and warehouses (w). The tactical model is in essence a multiproduct production and distribution problem formulated as a mixed integer program (MIP) whose constraints are:

$$\sum_j \sum_p Plant_{pjl} \le Totland_l \quad \text{all } l \text{ where } l \in L,\ p \in TP(j,l) \text{ and } j \in J \tag{1}$$

$$\sum_j \sum_p \sum_l Cplant_{jl} \cdot Plant_{pjl} \le Totinvest \tag{2}$$

$$\sum_j \sum_p \sum_l Water_j \cdot Plant_{pjl} \le Totwater \tag{3}$$

$$Min_j \cdot Y_{jp} \le Plant_{pjl} \le Max_j \cdot Y_{jp} \quad \text{all } j, p \text{ and } l \tag{4}$$

$$Harvest_{phjl} = Yield_{phjl} \cdot Total_{pjl} \cdot Plant_{pjl} \quad \text{all } p, h, j, l \text{ where } h \in TH(j,l) \tag{5}$$

$$\sum_f SP_{phjlf} = Harvest_{phjl} \quad \text{all } p, h, j, l, \text{ where } f \in PF \tag{6}$$

$$\begin{aligned} MenL_{tl} + MenT_{tl} \ge{} & \sum_{pj} MenP_{ptj} \cdot Plant_{pjl} \\ & + \sum_{pjl} MenH_{phj} \cdot Harvest_{phjl} \quad \text{all } t, l \text{ where } h = t \end{aligned} \tag{7}$$

$$Hire_{tl} + Fire_{tl} = MenL_{tl} - MenL_{t-1l} \quad \text{all } l \text{ and } t < t_m \tag{8}$$

$$Hire_{t_m l} + MenL_{t_m -1l} \ge MenL_{tl} \quad \text{all } l \text{ and } t_m \le t \tag{9}$$

$$Hire_{tl} \le Mfix,\ MenT_{tl} \le Maxtemp \quad \text{all } t, l \tag{10}$$

$$\begin{aligned} & Pack_{hkqf} = Color_{hkq} \sum_{phjk} (1 - Salv_{phjl}) SP_{phjlf} \cdot Prod_{phjk} / Weight_k \\ & \quad \text{all } h, f, k \text{ where } k \in K(j) \end{aligned} \tag{11}$$

$$HourF_{hf} \ge \sum_k HourL_k \cdot Pack_{hkf} \quad \text{all } h, f \text{ where } t = h \tag{12}$$

$$SK_{hj} = \sum_l \sum_p Salv_{phjl} \cdot Harvest_{phjl} \quad \text{all } j, h \tag{13}$$

$$Pack_{hkqf} = \sum_i SC_{t_1kqfir} + \sum_d SPD_{ht_2kqfdr} + \sum_w SPW_{ht_3kqfwr}$$

$$\text{all } h, f, k \text{ where } t_1 = h + Time_{fir}, t_2 = h + TimePW_{fwr}, t_3 = h + TimePD_{fdr} \quad (14)$$

$$Invw_{htkqw} = Invw_{ht-1kqw} + \sum_f SPW_{htkqfwr} - \sum_i SW_{ht_4kqwir} - \sum_d SWD_{ht_5kqwdr} + Z_{tkw}$$

$$\text{all } t >= h, k, w \text{ where } t_4 = t + TimeW_{wir}, t_5 = t + TimeWD_{wdr} \quad (15)$$

$$Invd_{htkqd} = Invd_{ht-1kqd} + \sum_f SPD_{htkqfdr} - \sum_i SD_{ht_6kqdir} + \sum_w SWD_{htkqwdr}$$

$$\text{all } t >= h, k, d \text{ where } t_6 = t + TimeD_{dir} \quad (16)$$

$$\sum_h \sum_k Invd_{htkqd}/Pallet_k \leq Dcap_d \quad \text{all } t, d \quad (17)$$

$$\sum_h \sum_k Invw_{htkqw}/Pallet_k \leq Wcap_w \quad \text{all } t, w \quad (18)$$

$$\sum_k Pack_{hkqf} \leq PFcap_f \quad \text{all } h, f \quad (19)$$

$$\sum_f SC_{tkqfir} + \sum_h \sum_w SW_{htkqwir} + \sum_h \sum_d SD_{htkqdir} = Dem_{tki}$$

$$\text{all } t, k, i, \text{ where } t \leq h \leq t - SL_k \text{ and } q \leq Qmax_i \quad (20)$$

$$Time_{fir} \cdot TC_{tkfir} \leq LT_i \quad \text{all } t, k, f, i, r \quad (21)$$

$$TimeW_{wir} \cdot TW_{tkwir} \leq LT_i \quad \text{all } t, k, w, i, r \quad (22)$$

$$TimeD_{dir} \cdot TD_{tkdir} \leq LTu_i \quad \text{all } t, k, d, i, r \quad (23)$$

Constraints (1)–(4) represent the main resources limiting the operations. Usually these resources are the result of strategic decisions such as total water and land available. In particular, constraints (1), (2) and (3) make sure that the resources used by a solution do not exceed the total availability of land, capital and water. Constraint (4) invokes the lower and upper bounds for the planting area for each crop per period. This is determined based on the farmers' previous commitments such as predetermined contracts with buyers. Constraint (5) limits the quantity to harvest to the hectares planted. Since some crops can be harvested for multiple periods, $Yield_{phjl}$ provides the expected yield of harvest for a given planting (p) and harvesting period (h), and $Total_{pjl}$ provide the expected yield for all the weeks for those crops planted in period p. Equation (6) is a transportation restriction that directs the harvested crops to the most convenient packaging facility according to their transportation cost. Equation (7) ensures that there are enough workers available for planting and harvesting during the time period. Equation (8) handles the hiring decision for seasonal workers, who can be hired incrementally according to the labor requirements. There is also a restriction on the last time period to hire these workers (9), since, after period t_m, the hiring of workers dwindles. There is also a restriction on the maximum number of seasonal and temporal workers to hire (10).

Constraint (11) models the packing of crops which change from weight units to packaging units at the packing facilities. Equation (12) ensures there are enough workers for processing the required products at the packing facility. In constraint (13), we estimate the percentage of crops that need to be salvaged because of substandard quality. In (14) the products are sent to storage in warehouses (*SPW*) and DCs (*SPD*) or directly to customers (*SC*). Constraint (15) provides conservation of flow for the warehouses, which can receive cargo from packing facilities (*SPW*) and ship to DCs (*SWD)* or directly to customers (*SW*). Equation (16) is the conservation of flow restriction for DCs, which can only ship to customers (*SD*) or receive cargo from warehouses (*SWD*) and packing facilities (*SPD*). Equations (17), (18) and (19) are capacity restrictions for warehouses and DCs and packing facilities. Equation (20) assures that customer demands are satisfied, using products that have been harvested in a period that observes their maximum storage time and that comply with the maximum color (*Qmax*) accepted by the customer. Constraints (21) to (23) restrict the lead-time of the last leg of transportation to be less than a predetermined delivery time imposed by the customers. The size of the problem described is multiplicative in nature and depends on the number of crops to grow, the planning periods and the options for transportation modes and final destinations, among some others. In the next section we present some experiments regarding different crops and distribution requirements to demonstrate how it affects the size of the problem to solve.

The objective of the MIP model is to maximize profits. The first part of the objective function represents the revenue obtained by prices of the products shipped to the customers, plus the revenue obtained by salvaging the unshipped crops minus the costs of transportation, planting, harvesting, holding and purchasing products from other vendors. This first part of the objective function is given by:

$$
\begin{aligned}
\text{Max} \sum_{tki} Price_{tki} \left(\sum_{f} SC_{tkfir} + \sum_{h}\sum_{w} SW_{htkwir} + \sum_{h}\sum_{d} SD_{htkdir} \right) \\
+ \sum_{hj} Psalvage_{j} SK_{hj} \\
- \sum_{tkqfir} CT_{fir} SC_{tkqfir} - \sum_{htkqwir} CTW_{wir} SW_{htkqwir} \\
- \sum_{htkqdir} CTD_{dir} SD_{htkqdir} - \sum_{htkqfwr} CTPW_{fwr} SPW_{htkqfwr} \\
- \sum_{htkqfdr} CTPD_{fdr} SPD_{htkqfdr} - \sum_{htkqwdr} CTWD_{wdr} SWD_{htkqwdr} \\
- \sum_{fhk} (Ccase_{k} + Coper_{k}) Pack_{hfk} - \sum_{pjl} Cplant_{jl} Plant_{pjl} \\
- \sum_{pjl} CLabor \cdot MenL_{tl} - \sum_{tl} Chire \cdot Hire_{tl} - \sum_{tl} Ctemp \cdot MenT_{tl} \\
- \frac{1}{40} \sum_{tf} CLabor \cdot HourL_{tf} - \sum_{tkw} Chw_{kw} Invw_{tkw} \\
- \sum_{tkd} Chd_{kd} Invd_{tkd} - \sum_{tkw} Pavg_{tk} Z_{tkw}
\end{aligned}
\tag{24}
$$

The second part of the objective function is a loss function for the decay of the products while being transported by the different transportation modes. This function is given by:

$$
\begin{aligned}
&-\sum_{tkqfir} SC_{tkqfir} Price_{tki} Time_{fir}/SL_k \\
&\quad -\sum_{htkqwir} Price_{tki} TimeW_{wir} SW_{htkqwir}/SL_k \\
&\quad -\sum_{htkqfwr} Pavg_{tk} TimePW_{fwr} SPW_{htkqfwr}/SL_k \\
&\quad -\sum_{htkqfdr} Pavg_{tk} TimePD_{fdr} SPD_{htkqfdr}/SL_k \\
&\quad -\sum_{htkqwdr} Pavg_{tk} TimeWD_{wdr} SWD_{htkwdr}/SL_k \\
&\quad -\sum_{htkqdir} Price_{tki} TimeD_{dir} SD_{htkqdir}/SL_k
\end{aligned}
\tag{25}
$$

Equation (25) is a linear function that penalizes the transportation time according to the prices of the products (Fig. 1). Decay of the product is estimated based on the type of transportation link used. We use the value to the final customer ($Price_{tki}$) for final delivery transportation links (*SD*, *SW*, and *SC*). For the rest of the transportation links we use the average FOB (Free on Board) value of the crops ($Pavg_{tk}$).

3.4 Structure of the model and computational results

One potential issue in solving model (1)–(25) is that it can easily grow very large, given the different options of crops, planting locations, harvesting decisions, and the behavior of each of the potential markets. All these different combinations cause the size of the problem to grow exponentially. The complexity of the problem is compounded by the planting and variety selection decisions, which are modeled with integer variables (Wolsey 1998), since each integer solution leads to a different planting and distribution structure. However the structure of the problem has some characteristics that can render it suitable for the use of decomposition methods. For instance, once the binary decision variables are set to particular values, the combination of production, storage and transportation decisions in the present model form a characteristic staircase pattern, which very often leads to the application of computationally efficient decomposition methods. Another feature of the problem is that the distribution decisions can be modeled as a multi-commodity flow problem. In particular, transportation variables can be represented by a minimum cost network flow problem with uncapacitated arcs. This particular property transforms the selection of the transportation decisions into a minimum spanning tree problem (Ahuja et al. 1993). The selection of the spanning tree is only dependant on the cost of transportation for available transportation links, which are those that have not been precluded by lead time or shelf life restrictions.

In order to test the proposed model, we used several instances of the planning problem with different combinations of crops to plant and distribution structure. The model was solved using CPLEX 10.0 on a Pentium 4 machine with 2GB of Memory. The factors considered in the evaluation were the number of crops (J), periods (T), production periods (*TP*), harvest periods (*TH*), customers (I), locations (L), plants (P), warehouses (W), DCs (D),

Table 2 Results from the experiments

J	T	TP	TH	I	L	P	W	D	K	H	Row	Col	Non	Binary	Gap	Time
8	30	8	15	3	2	2	2	2	8	3	64,106	71,242	233,055	12,304	0.0%	42
8	30	8	16	100	2	2	2	10	8	1	22,134	123,088	311,129	39,776	0.0%	58
8	40	18	26	3	2	2	2	2	8	3	9,639	40,384	124,379	15,424	0.1%	73
8	40	18	26	100	2	2	2	10	8	1	29,016	136,682	359,299	60,407	1.7%	3,600
35	40	18	26	3	2	2	2	2	8	3	25,222	77,162	319,583	19,510	2.8%	3,600
35	40	18	26	100	2	2	2	10	8	1	44,271	184,814	561,660	60,893	0.0%	3,299

products (K), and transportation modes (H). The results obtained for each experiment are presented in terms of CPU seconds (Time) and optimality gap (Gap) in Table 2. Other fields in Table 2 are related to the problem size including the number of rows in the model (Row), the number of variables (Col), the nonzero coefficients in the matrix (Non), and the number of binary variables (Binary).

From the experiments performed, it is evident that the growth in binary variables is the main contributor to the total processing time observed. In particular, those related to the selection of crops (J), which form a knapsack problem that is inherently hard to solve. However, the source of the complexity of the problem might change if the resolution for the decision variables is changed from weeks to days; then, the number planting and harvesting variables would increase greatly, with a consequent increase of the running time and size of the problem. A further reduction in running times could be explored by exploiting the structure of the model to use decomposition algorithms, such as Bender's decomposition to decrease the processing time required by larger instances such as those with more distribution points, customers and products, which might make this planning problem very time consuming. Exploration of other solution alternatives is left as future research. We now focus the validation of the proposed model on the impact of the results on the operations of a grower/shipper.

4 Validation and case study

To validate our model, we prepared a plan for planting, harvesting, and distributing the crops of a hypothetical producer who is based in the northwest region of Mexico and exports most of its produce to the US winter market. The model results in a plan that covers the entire growing season, from the time the crops are planted until the last day of harvest. We assume that the grower produces two crops: green bell peppers and vine ripe tomatoes.

To estimate production yields from these crops, we used publicly available data (Table 3) given by third party providers. This data is usually generated through field experiments ran by universities and growers associations and performed every year to test new varieties that come into the market (Arellano 2001). Table 3 indicates the expected yield (in pounds) for four different varieties (A–D) of vine ripe tomatoes. The harvested fruit can have different sizes (4×4, 4×5, as shown in Table 3) and qualities according to the classification of USDA (1991).

To obtain the costs of labor, seeds, fertilizer and agrochemicals used, we use data from a government study that interviewed producers in the State of Sinaloa (FIRA 2007). We also gathered the transportation cost and the estimated travel time for the three main transportation modes within North America: truck, rail and air. This information was obtained

Table 3 Yield per hectare of tomatoes

Variety	Pounds per hectare of tomato						
	4 × 4	4 × 5	5 × 5	5 × 6	6 × 6	6 × 7	Total
A	27,623	42,320	18,745	13,133	1,978	667	104,466
B	17,641	32,200	37,697	34,592	5,129	1,012	128,271
C	16,629	31,947	39,606	41,170	7,981	1,518	138,851
D	2,990	15,709	33,442	63,342	24,150	8,280	147,913

Table 4 Transportation data for Warehouse-DC links

Warehouse	DC	Trans Mode	Time (Weeks)	Cost/Pack
W1	D1	TRUCK	0.49	$1.73
W1	D1	AIR	0.14	$31.25
W1	D1	RAIL	0.71	$1.25
W1	D2	TRUCK	0.14	$0.50
W1	D2	AIR	0.14	$13.02
W1	D2	RAIL	0.29	$0.40
W2	D1	TRUCK	0.40	$1.39
W2	D1	AIR	0.14	$20.83
W2	D1	RAIL	0.43	$0.81
W2	D2	TRUCK	0.43	$1.24
W2	D2	AIR	0.14	$29.69
W2	D2	RAIL	0.71	$1.18

from public sources that include trucking transportation rates published by USDA (2006). For the case of railroad and air transportation we used interviews with providers of these services, these interviews were performed by Sanchez (2007). Table 4 presents a sample of the transportation data, which includes the transportation links between the warehouses and the distribution centers and the corresponding times and costs. We assume the warehouses are located in Nogales (W1) and McAllen (W2) and the distribution centers are located in Chicago (D1) and Los Angeles (D2). Time is given in weeks and the cost per pack is the prorated cost for a given product (Ex. 1920 boxes per truck). We developed tables similar to these for all combinations of transportation links.

A major decision presented by the model is the timing of planting and harvesting to satisfy customer demand. In order to satisfy these requirements, we developed a matrix of the potential planting dates and the expected harvesting days using the information provided from Robles and Santana (1997) and Arellano (2001), which is presented in Table 5 for one of the tomato crops (variety A), and a similar matrix is developed for all the varieties being considered.

The market information include the FOB prices of the "shipping points" of crops (Table 6) published by USDA (2007), which provides information for several types of standardized packages for tomato and other crops (e.g. 4 × 4). In addition to the FOB prices, we also gathered prices for two "terminal markets" (Chicago and Los Angeles), which we used to represent other customers. For this example we gathered the information for the years

Table 5 Plant and harvest matrix for Crop A

Week	15	16	17	18	19	20	21	22	23	24	25	26	27	29	29	30	Total
1	0.01	0.07	0.17	0.17	0.20	0.04	0.10	0.05	0.07	0.04	0.08						1.00
2		0.01	0.07	0.17	0.17	0.20	0.04	0.10	0.05	0.07	0.04	0.08					1.00
3			0.01	0.07	0.17	0.17	0.20	0.04	0.10	0.05	0.07	0.04	0.08				1.00
4				0.01	0.07	0.17	0.17	0.20	0.04	0.10	0.05	0.07	0.04	0.08			1.00
5					0.01	0.07	0.17	0.17	0.20	0.04	0.10	0.05	0.07	0.04	0.08		1.00
6							0.11	0.06	0.09	0.22	0.26	0.08	0.04	0.06	0.03	0.06	1.00

Table 6 Price in dollars per box of tomatoes (23 lbs per box)

Year	4 × 4	4 × 5	5 × 5	5 × 6
1998	9.86	9.87	8.49	7.59
1999	7.71	7.71	6.59	5.93
2000	7.87	7.87	6.82	6.36
2001	9.54	9.54	7.59	6.73
2002	10.85	10.85	8.78	7.74
2003	10.01	9.93	8.40	7.71
2004	11.05	11.05	9.58	8.54
2005	13.40	13.40	11.55	10.61
Average	10.01	10.00	8.45	7.62

1998–2005 on a weekly basis and obtained the expected prices for the season by adjusting prices for the inflation during those same years.

The proposed supply chain of the grower includes two locations for planting, a total of area of 500 hectares divided in two locations, two packing facilities, two potential warehouses, three customers and two distribution centers. We also set the maximum crop storage time, with the help of previous studies (Welby and McGregor 2004). For tomatoes, we set the maximum storage life to one week; and for peppers, two weeks. We also set the maximum cycle time for delivery to the final customer to be one week (both peppers and tomatoes), which is a common service requirement for agricultural industries (Perosio et al. 2001).

We modeled the problem with the aid of the AMPL modeling language in conjunction with CPLEX® Solver version 10.0. The planting schedule recommended by the model is presented in the Table 7. This table displays the crop selection, timing of planting and amount of hectares of each crop to plant. Tomato varieties B and D (TCB and TCD) were selected and the bell pepper variety D (CCD). According to these results, the growers should plant 28 hectares of bell peppers of variety D in the first week of production. Also relevant is the 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 complementing the planting in the last periods (16–17).

The model prescribes direct distribution to customers in terminal markets and FOB deliveries at warehouses in the border city of Nogales. Results suggest that by changing from their current strategy (FOB sales) to one with direct deliveries to final customers, grower-shippers can increase their revenues by about 25%. These results are very promising, even when considering the additional risk of handling perishable products for a larger period of time than with FOB sales. As part of the validation of the model, we shared the resulting

Table 7 Crop selection and planting period

Week	Crops selected			
	CCD	TCB	TCD	Week total
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	–	88	–	88
Crop total	93	354	53	500

Table 8 Boxes of product shipped for the base case

From	Truck			Air			Rail		
	C1	C2	C3	C1	C2	C3	C1	C2	C3
Warehouse	806,989	112,198							
DC		21,538	226,193						
Packhouse	1,045,116						7,799		
Total	1,852,105	133,736	226,193				7,799		

planting and harvesting plans with growers, and they confirmed the feasibility of the recommendations.

The model also allows for targeted market segmentation, given the particular demands of each customer and the corresponding prices they are willing to pay. For instance, according to Table 8 the targeted production allocation should be 83% for FOB customers (C1), 10% for Chicago (C3) and the remaining 7% for Los Angeles (C2). This table also shows that trucking is the preferred transportation mode due to the lead time requirements and the penalty costs proportional to the traveling time. For terminal markets the model suggests using distribution centers for final delivery; but, for FOB sales, the preferred way is through sales at warehouses located at shipping points. The growers we consulted confirmed that these distribution patterns seem reasonable according to their experience in the different markets.

To estimate the effects of perishability, we developed three experiments with the same data, but eliminated some of the constraints and the second part of the objective function, which relates to perishable items. The results from these changes can be observed in Table 9. Scenario 1 relaxes the crop color restriction; scenario 2 eliminates the decay function and scenario 3 combines the two previous scenarios. From this table it is evident that the transportation plan shifts from sending most of the shipments to the closest customer, to customers located at further distances. The preferred transportation method also changes, depending on the inclusion of the decay function.

An additional benefit of the mathematical models used, is the possibility of performing sensitivity analysis. For example, it is possible to estimate the benefits of hiring more sea-

Table 9 Comparison of results with different perishable features

Scenario	From	Truck			Rail		
		C1	C2	C3	C1	C2	C3
1	Warehouse	774,860	82,839				
1	DC			716,021			
1	Packhouse	630,445					
	Total	1,405,305	82,839	716,021			
2	Warehouse	363,188				378,765	156,740
2	DC						
2	Packhouse				987,464		332,726
	Total	363,188			987,464	378,765	489,466
3	Warehouse	442,623				135,140	523,490
3	DC						
3	Packhouse				312,167		784,398
	Total	442,623			312,167	135,140	1,307,888

Table 10 Shadow prices of hiring additional personnel

Scenario	Dual price	
	Seasonal (US$)	Temporal (US$)
1	7,040	5,400
2	9,280	6,883
3	10,302	7,246
4	7,161	3,837

sonal and temporary workers, as shown in Table 10. In this table the first three scenarios are those from the previous table and scenario 4 is the current model with all of the perishability restrictions and functions. Table 10 presents the shadow prices for seasonal and temporary workers, which indicates the maximum contribution, if it were possible to hire extra workers. The contribution of seasonal workers is given by the extra production given by an additional worker and by replacing the more expensive temporary workers in several periods during the season. However, the contribution of temporary workers is only valid for those periods in which the amount to harvest is constrained by the number of available workers, which is small in the season. A similar analysis can be undertaken to determine the robustness of the current results; for example, what are the benefits of using one variety over another, or the benefits of having a distribution center or a warehouse in a certain region. Such information can provide growers with better tools regarding the potential changes in their current tactical plans.

5 Conclusions and future research

This paper presented a model to perform the tactical planning for a grower/shipper of fresh produce. This model is our first attempt at tackling the complicated planning problem of the management of the supply chain of fresh produce. As it demonstrates, the planning of fresh produce not only requires the selection and timing of crop planting, but also the decay of fresh products and labor management issues. From the perspective of the results of the case study, the model suggests that the current strategy of using mostly truck for moving highly perishable crops is adequate, given the high value of these crops and the potential loss incurred during transportation.

The paper also explored the current distribution tactic used by the growers, and compared it to one based on direct distribution of products. The revenues obtained by direct distribution are significantly higher than those that result from current practice. The benefits of direct distribution are part of the reason why some large, fresh-produce growers are getting involved in the distribution of their crops. Furthermore, through the research reported in the literature and our interviews with producers, we have found that there is currently a need for integrated planning tools that support decisions made by growers/shippers. The tools proposed in this paper can help them to succeed in a very complex supply chain, such as the one for fresh agricultural commodities. As demonstrated through the case study, the use of these tools has the potential of improving significantly the revenue obtained by the potential users.

In addition, we believe that the proposed model is particularly well suited for the case of contracted production, in which growers have fixed volume commitments, or have agreed on a certain price for their products, or some combination of both. Using the present model, growers can determine their growing, labor and transportation requirements throughout the season. Growers can also use it to determine their most profitable customers, not only based on the prices they pay, but also based in their transportation requirements and other conditions, such as quality and service, that they impose.

Some of the areas for further expansion of the present tactical model include:

1. Incorporate capital or investment options, such as renting or buying more land or more equipment.
2. Explore the use decomposition algorithms, such as Bender's decomposition to decrease the run time to solve for larger-instances.

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Appendix A

Indexes and sets

$l \in L$	Locations available for planting
$t \in T$	Planning periods (weeks)
$j \in J$	Potential crops and/or varieties to plant
$p \in TP(j,l) \subseteq T$	Set of feasible planting weeks for crop j in location l
$h \in TH(j,l) \subseteq T$	Set of feasible harvesting weeks for crop j in location l
$k \in K(j)$	Products obtained from crop j
$q \in Q$	Quality of crop at harvest (color)
$w \in W$	Warehouses available for storage
$i \in I$	Customers
$d \in D$	Distribution centers

$f \in PF$	Packaging facilities
$r \in TM$	Transportation mode

Parameters

$Water_j$	Water required per acre of crop j in cubic meters (in cubic meters)
$Totland_l$	Land available at location l (in hectares)
$Wcap_w$	Capacity of warehouse w (in pallets)
$Dcap_d$	Capacity of DC d (in pallets)
$PFcap_f$	Capacity of packing facility f (boxes per week)
$ShelfL_k$	Shelf life of product k (in weeks)
$LeadT_i$	Required lead time by customer i (in weeks)
$MenP_{ptj}$	Workers required at period t for cultivating crop j planted at period p (men-week/Ha)
$MenH_{phj}$	Workers required at period t for harvesting crop j planted at period p (men-week/Ha)
$HourL_K$	Man-hours required for packing a box of product k
$Yield_{phjl}$	Yield of crop j planted in location l at time p and harvested in week h (percentage of total)
$Total_{pjl}$	Total production of crop j planted in location l at time p (pounds per hectare)
$Prod_{phjk}$	Percentage of product k from crop planted in location l at time p harvested in week h (percentage)
$Salvage_{phjl}$	Percentage of salvaged crop j planted in location l at time p harvested in week h
$Weight_k$	Quantity of crop j required to pack a box of product k (in pounds)
$Pallet_k$	Boxes of product k required to form a pallet
Max_j	Maximum amount to plant of crop j (in hectares)
Min_j	Minimum amount to plant of crop j (in hectares)
$Totlabor$	Maximum number of contracted seasonal workers available (men-week)
$Maxtemp$	Maximum number of temporal day laborers available (men-day)
$Color_{hjq}$	Percentage of harvested fruits with color q from crop j at period h
$Qmax_i$	Higher level of color in the product to send to customer i (colors 3–6)
$Demand_{tki}$	Number of boxes of product k demanded by customer i at time t (boxes per week)
$Totinvest$	Investment quantity available (dollars)
$Totwater$	Water restriction (in cubic meters)
M	Large quantity to prevent shipment if route is not selected

Cost parameters

$Price_{tki}$	Price for the grower of a box of product k sold to customer i at time t
$Psalv_j$	Salvage value of a pound of crop j
$Pavg_{tk}$	Price on the open market for a box of product k at period t
$Cplant_{jl}$	Cost per hectare of production for crop j planted in location l
$Ctemp$	Cost of one man-day for day-laborers

$Clabor$	Cost of seasonal laborers per man-week
$Ccase_k$	Cost to package a box of product k
$Chire$	Fixed cost of hiring a seasonal laborer at the field site
$Coper_k$	Cost of labor for packing a box of product k
Chw_{kw}	Holding cost of a pallet of product k in warehouse w
Chd_{kd}	Cost to hold a pallet of product k in DC d

Transportation parameters

$Time_{fir}$	Transit time from facility f to customer i using transportation mode r
$TimeW_{wir}$	Transit time from warehouse w to customer i using transportation mode r
$TimeD_{dir}$	Transit time from DC d to customer i using transportation mode r
$TimePW_{fwr}$	Time from packing facility f to warehouse w using transportation mode r
$TimePD_{fdr}$	Transit time from packing facility f to DC d using transportation mode r
$TimeWD_{wdr}$	Transit time from warehouse w to DC d using transportation mode r
CT_{fir}	Cost of transportation from packing facility f to customer i using transportation mode r
CTW_{wir}	Cost of transportation from warehouse w to customer i using transportation mode r
CTD_{dir}	Cost of transportation from DC d to customer i using transportation mode r
$CTPW_{fwr}$	Cost of transportation from packing facility f to warehouse w using transportation mode r
$CTPD_{fdr}$	Cost of transportation from packing facility f to DC d using transportation mode r
$CTWD_{wdr}$	Cost of transportation from warehouse w to DC d using transportation mode r

Variables

$Plant_{pjl}$	Area to plant of crop j, in period p at location l (in hectares)
$Harvest_{phjl}$	Harvest (pounds) of crop j in period h and planted in period p at location l
$Pack_{hkqf}$	Quantity of product k with color q packed at facility f in period h (in boxes)
$MenL_{tl}$	Seasonal laborers required at location l and time t (men-week)
$HourF_{hf}$	Operator hours allocated at facility f and harvest time h
$Hire_{tl}$	Number of workers hired at period t in location l
$Fire_{tl}$	Number of workers terminated at period t in location l
$MenT_{tl}$	Number of temporal laborers hired at period t in location l (men-week)
SP_{phjlf}	Pounds of crop j to ship from location l to facility f in period h
SC_{tkqfir}	Boxes of product k with color q shipped to customer i from facility f in period t by transportation mode r

$SPD_{htkqfdr}$	Boxes of product k harvested in period h with color q shipped from facility f to DC d in period t by transportation mode r
$SPW_{htkqfwr}$	Boxes of product k harvested in period h with color q shipped from facility f to warehouse w in period t by transportation mode r
$SD_{htkqdir}$	Boxes of product k harvested in period h with quality q shipped from facility f to DC
$SWD_{htkqwdr}$	Boxes of crop k harvested in period h with color q shipped from warehouse w to DC d in period t by transportation mode r
$SW_{htkqwir}$	Boxes of product k harvested in period h with color q shipped from warehouse w to customer i in period t by transportation mode r
$Invw_{htkqw}$	Stored boxes of product k harvested at period h with color q in warehouse w in period t
$Invd_{htkqd}$	Stored boxes of product k harvested at period h with color q in DC d at period t
SK_{hj}	Surplus of crop j at time h in the field (in pounds)
Z_{tkw}	Boxes of product k to purchase in period t for warehouse w
TC_{tkfir}	Transportation mode r selected for transporting product k from f to i at time t, 1 if selected, 0 otherwise
TPW_{tkfwr}	Transportation mode r selected for transporting product k from f to i at time t, 1 if selected, 0 otherwise
TWD_{tkwdr}	Transportation mode r selected for transporting product k from w to d at time t, 1 is selected, 0 otherwise
TPD_{tkfdr}	Transportation mode r selected for transporting product k from f to d at time t, 1 is selected, 0 otherwise
TW_{tkwir}	Transportation mode r selected for transporting product k from w to i at time t, 1 is selected, 0 otherwise
TD_{tkdir}	Transportation mode r selected for transporting product k from d to i at time t, 1 is selected, 0 otherwise
Y_{jpl}	1 if crop j is planted at period p at location l, 0 otherwise

Here

$$Y, TC, TPW, TWD, TPD, TW, TD \in B^n$$

$$Plant, Harvest, Pack, Opl, Opf, Hire, Fire, Opt, K, Z \in R_+^n$$

$$SP, SPD, SPW, SD, SWD, SW, Innw, Invd \in R_+^n$$

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