

## **Supply Chain Strategies for Perishable Products: The Case of Fresh Produce**

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### **Abstract**

This paper examines supply chain design strategies for a specific type of perishable product—fresh produce, using melons and sweet corn as examples. Melons and other types of produce reach their peak value at time of harvest; product value deteriorates exponentially post-harvest until the product is cooled to dampen the deterioration. Using the product's *marginal value of time*, the rate at which the product loses value over time in the supply chain, we show that the appropriate model to minimize lost value in the supply chain is a hybrid of a responsive model from post-harvest to cooling, followed by an efficient model in the remainder of the chain. We also show that these two segments of the supply chain are only loosely-linked, implying that little coordination is required across the chain to achieve value maximization. The models we develop also provide insights into the use of a product's marginal value of time to develop supply chain strategies for other perishable products.

**(Supply Chain Management; Perishable Products; Fresh Produce; Marginal Value of Time; Harvest Strategy)**

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# Supply Chain Strategies for Perishable Products: The Case of Fresh Produce

## 1. Introduction

This paper considers the problem of designing and managing effective supply chains for a specific type of perishable product, fresh produce. The challenge for managing fresh produce is that product value deteriorates significantly over time in the supply chain at rates that are highly temperature and humidity dependent. We show that these changes in product value make conventional supply chain strategies inappropriate.

For many products, a decision about supply chain strategy involves a choice between responsiveness and efficiency. The appropriate choice depends on how the product changes in value over the time interval between production and delivery to the customer. To clarify, we define the term *marginal value of time* (MVT) to be the change in value of a unit of product per unit time at a given point in the supply chain. MVT measures the cost of a unit time delay in the supply chain. When the MVT remains relatively stable over time in the supply chain, then a single design choice of either responsiveness or efficiency is appropriate. However, for fresh produce, we show that because of dramatic changes in the MVT and hence in the cost of time delays, no single design choice is appropriate for the entire chain.

In this study, we develop a hybrid strategy that is a combination of speed and efficiency. We use fresh melons and sweet corn as representative examples of perishable products because they exhibit a rapid decline in value over time under certain conditions and have limited shelf-life. We also model the effects on supply chain performance of actions taken to decrease the loss in value due to perishability. The results we obtain

offer useful insights for using the MVT of a product to optimize supply chain performance.

The structure of the paper is as follows. First, we present a review of relevant literature. The third section describes the problem of maximizing value in the supply chain for fresh melons and sweet corn along with a summary of design strategies that have been suggested for conventional supply chains. We then reinterpret those strategies in terms of the MVT in supply chains and show that the appropriate supply chain for these products is a hybrid of conventional strategies. Finally, we analyze the specific design problems posed in different segments of the supply chain and discuss implementation issues.

## **2. Literature Review**

In developing supply chain strategies for perishable food products, we build upon two distinct research streams: models for perishable inventory management and supply chain design structures. We summarize the most relevant research in each of these streams and integrate the concepts into a more general model for the supply chain for perishable products.

Numerous models for managing the inventory of a perishable product have been developed (see Nahmias (1982) for a thorough review of the early literature). Of particular relevance to the current study are models that deal with degradation of product quality and value over time. In most early studies on perishable inventory, perishability is defined as the number of units of product that outdate (perish). Hence, the decay is not in terms of value, but in the number of units, and the decay is modeled with a probability distribution. For example, Ghare and Schrader (1963) develop an EOQ

model for products in which the number of usable units is subject to exponential decay. Covert and Philip (1973) and Philip (1974) extend this model, but use the Weibull distribution to model item deterioration. Shah (1977) extends the model to allow for shortages and backlogging, and Tadikamalla (1978) examines the case of Gamma-distributed deterioration. Giri and Chaudhuri (1978) and Chakrabarty et al. (1978) extend these models to include situations in which demand rate is dependent upon either the inventory level or time.

Some papers do consider deterioration in product *value* over time. Weiss (1982) examines a situation where the value of an item decreases non-linearly the longer it is held in stock. Fujiwara and Perera (1993) develop EOQ models for inventory management under the assumption that product value diminishes over time according to an exponential distribution. However, they assume that the rate of deterioration of product value *increases* with the age of the inventory. Goh (1994) allows holding cost to vary based upon on-hand inventory levels. More recently, Ferguson et al. (2006) apply Weiss' model to optimal order quantities for perishable goods in small to medium size grocery stores with delivery surcharges. Research on the perishability of fresh produce indicates that, unlike these models, the loss in product value and quality is at its highest rate immediately post-production (at harvest), and the *rate* of loss in value declines until the produce finally "spoils" (Hardenburg et al. 1986, Appleman and Arthur 1919). Using this information, we extend the EOQ models for perishable inventory.

To date, the perishability models that have been developed only consider inventory management: determining appropriate levels of perishable stock to meet demand. Ferguson and Ketzenberg (2006) and Ketzenberg and Ferguson (2008)

examine the value of information sharing between retailers and suppliers for perishable products. The first study considers a supplier sharing age-dependent information with retailers, and the more recent paper considers the sharing of information on ageing and demand by the retailer with the supplier. Ferguson and Koenigsberg (2007) study the effects of firms selling leftover perishable products at a lower price in competition with fresh product. But no studies consider broader supply chain design issues, which are the focus of this paper. We build a model of perishability for fresh produce to examine how these products should be managed throughout the supply chain.

A number of frameworks have been proposed for supply chain design. One of the first was introduced by Fisher (1997), who devises a taxonomy for supply chains based on the nature of the demand for the product. For *functional* products (stable, predictable demand, long life cycle, slow “clockspeed”) Fisher argues that the supply chain should be designed for cost efficiency; for *innovative* products (volatile demand, short life cycle, fast “clockspeed”) he maintained that the supply chain should be designed to be fast and responsive. Lee (2002) expands upon Fisher’s taxonomy by suggesting that the supply process could be either stable or evolving. A stable supply process has a well-established supply base and mature manufacturing processes. In an evolving supply process, technologies are still early in their development with limited suppliers. Kopczak and Johnson (2003) extend the framework to include coordination of activities across companies, improving information flows, and collaborative redesign of the supply chain as well as its products and processes.

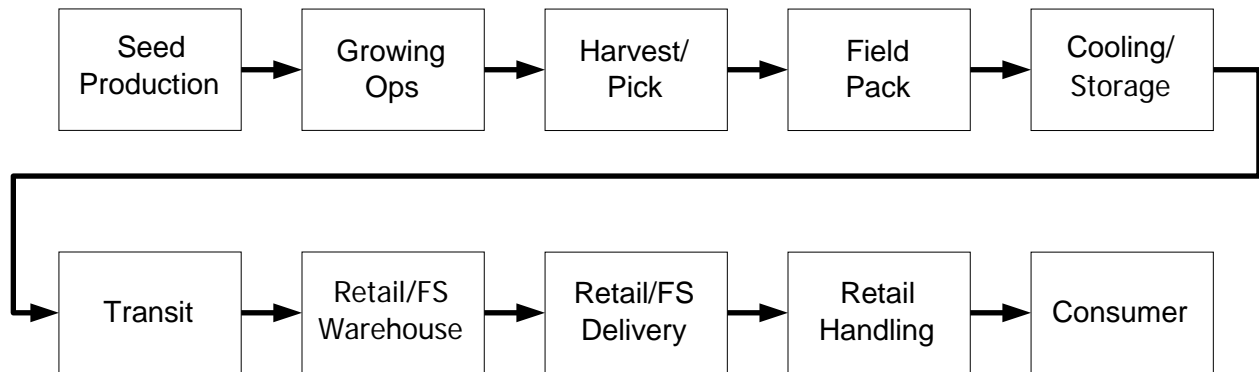
Feitzinger and Lee (1997) introduce the concept of delayed product differentiation, or *postponement*. They showed that delaying final product definition

until further downstream in the chain reduces variety in the early stages (in effect, making the product more functional). This creates opportunities for supply chain designs that can be *efficient* in the early stages and *responsive* in the final stages. In their studies of reverse supply chains, Blackburn et al. (2004) find that, for returned products that lose value rapidly over time, the supply chain should be *responsive* in the early stages and *efficient* in later stages. These studies suggest that supply chain strategies based on a simple choice between efficiency and response can be inappropriate when the product undergoes substantial differentiation or change in value as it moves through the chain. We show that this is the case for perishable produce: the value of the product changes significantly, and the appropriate supply chain structure is one that is responsive in the early stages and efficient in the later stages.

### **3. Managing the Supply Chain for Melons**

Figure 1 is a schematic of the sequence of activities in the supply chain for melons, from seed production to ultimate consumer purchase either through the retail or food service channels. For most fresh produce, the maximum quality (and value) of the product is largely determined by actions taken in the early stages of the process: seed production, growing conditions, planting practices, and harvesting methods. Value is typically defined by sugar levels which begin to deteriorate immediately upon harvest and the supply chain management problem is to control the loss in value over the remaining stages in the chain—from the field to the consumer. The focus of our study is optimization of the supply chain post-harvest; we do not explore the agricultural issues surrounding seed production and the growing operations.

**Figure 1**  
**A Schematic of the Melon Supply Chain**



In the large produce operations we have observed in California, melons and sweet corn are picked by hand and field packed, an extremely labor-intensive process. Melons are picked by multiple teams of workers (10-20 workers) who move through the field behind a trailer pulled by a tractor. As melons are picked, they are tossed to workers on the trailer who sort and pack them into cartons according to size (of up to 30 melons). Picking rates by a team average about 50-60 cartons per hour. Cartons are stacked onto pallets, 42 cartons per pallet, and trailers can hold about 12-14 pallets, or up to about 590 cartons of melons. Periodically, these pallets are transferred to a nearby truck. In the peak season, a truck is filled with melons in about three to four hours, with multiple teams harvesting a given field. When full, the truck is driven to the cooling shed, where the melons are hydro, forced-air or vacuum cooled to preserve product quality. The process for sweet corn is similar.

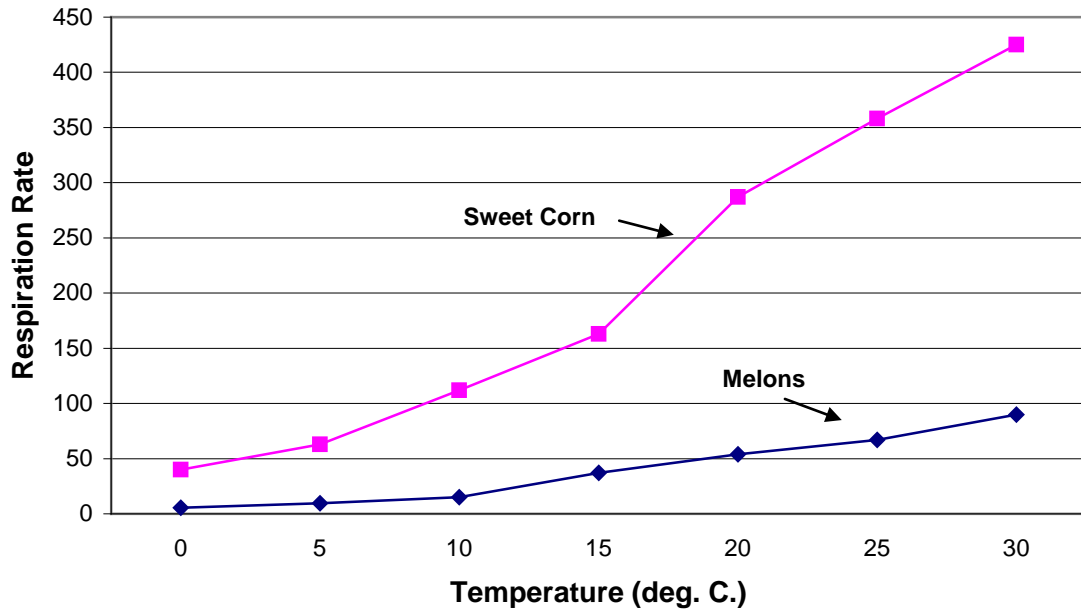
Cooling sheds are located throughout a growing region and serve as both a cooling facility and as a consolidation point for outbound truck shipments. Cooling sheds serve several growers in a region and are typically owned and operated separately from



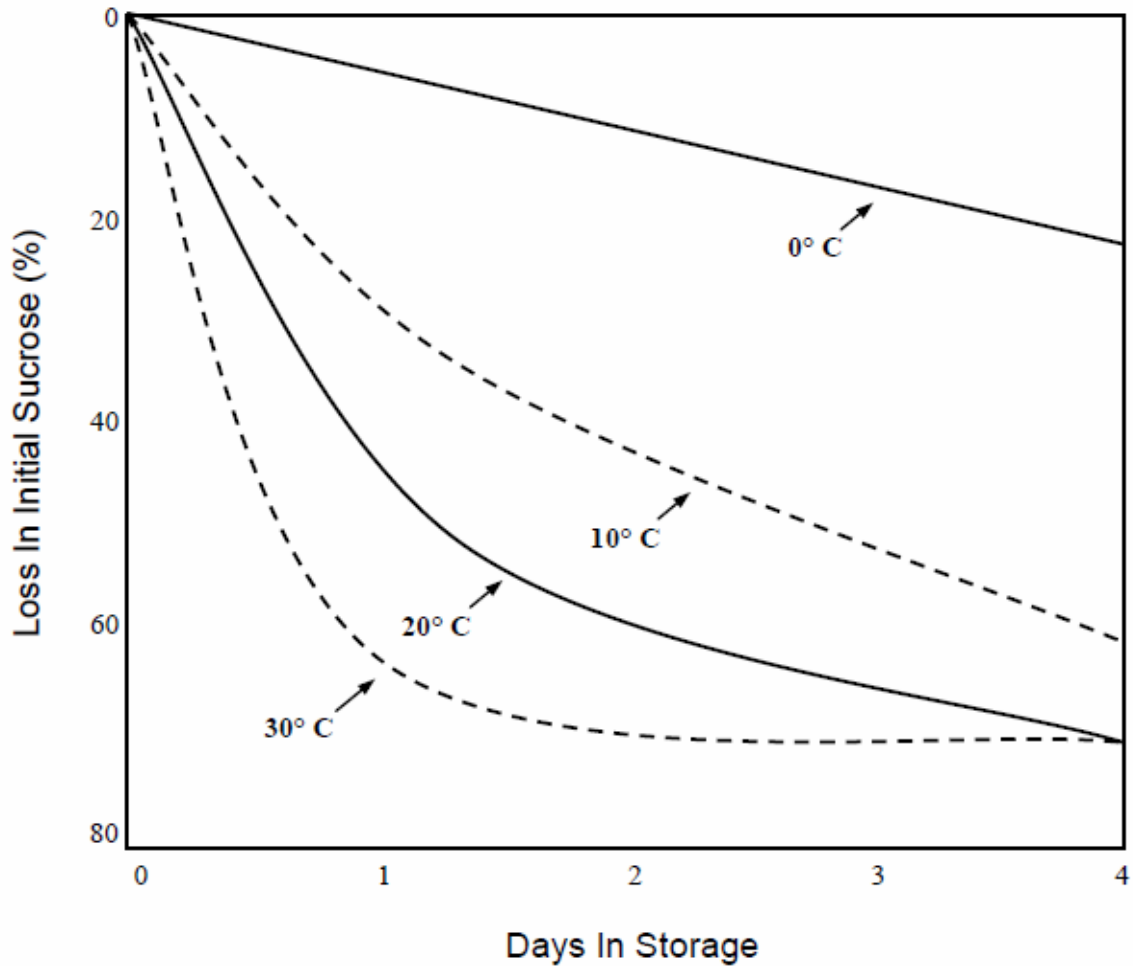
the growing operations. Thus, the location of these facilities is not considered here. The time and cost to transfer a batch of cartons from the field to the cooling shed depends on the location of the field. Transfer time to the cooling sheds is assumed to be independent of the transfer batch size, except in the unlikely event that the transfer batch size exceeds the capacity of the trailer. We neglect the small effects of batch size on the time to load and unload the batch. The time to transfer melons from the field to a cooling shed can vary from 15 minutes to an hour.

Freshly-picked produce begins a chemical process of respiration. Respiration not only generates carbon dioxide ( $\text{CO}_2$ ) and heat, but it also converts sugar to starch, causing the product to lose sweetness and quality. Figure 2 displays laboratory measurements of the rate of respiration for melons and sweet corn, showing that the respiration rate (and loss in sugar content) increases significantly with temperature (Hardenburg et al. 1986), and that sweet corn has higher respiration rates than melons. Appleman and Arthur (1919) (see Figure 3) show the effect of respiration on quality (and value) and that the loss of sweetness in corn over time follows an exponential decay function whose decay rate increases dramatically with temperature (melons exhibit a similar functional relationship between sweetness, time and temperature (Suslow, Cantwell and Mitchell 2002)).

**Figure 2**  
**Respiration Rate for Melons and Sweet Corn**  
**(Mg. CO<sub>2</sub>/kg. hr)**



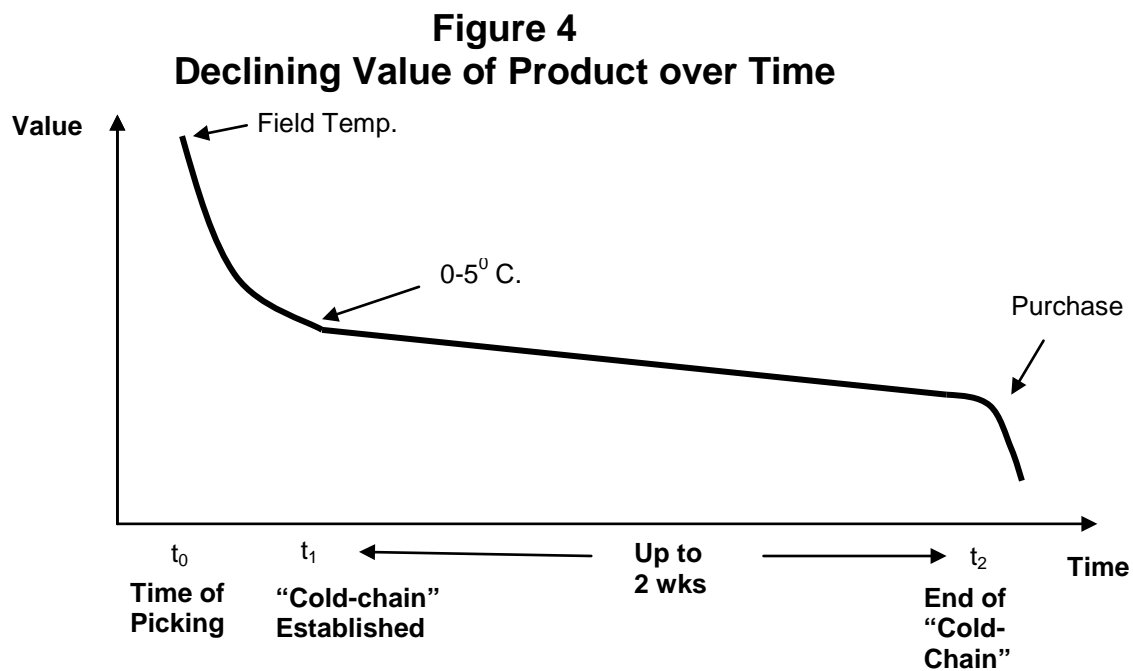
**Figure 3**  
**Sucrose Depletion in Sweet Corn**  
**At Four Temperatures**  
(Appleman and Arthur 1919)



Because freshly-picked produce can have an internal temperature reaching 30-35 degrees Centigrade, quickly removing field heat is critical to maintaining product quality. Therefore, it is very important to move the product rapidly from the field to a cooling shed to preserve product quality (Jobling 2002 and Sargent et al. 2000). Hartz, Mayberry and Valencia (1996) observe that rapid removal of field heat maximizes post-harvest life. Once the melon or corn reaches the cooling shed and has been cooled to a temperature a

few degrees above freezing, product deterioration occurs at a much lower rate. The product value (its taste and appearance) can be maintained for several weeks, provided that the “cold chain” is maintained throughout the remaining stages of the chain (Perosio et al. 2001).

We consider how to minimize total cost in the entire post-harvest time interval: before and after the “cold chain” is established. In doing so, we seek to maximize the value of the product delivered to the customer, net of the cost of managing the supply chain process. Figure 4 shows schematically how the typical product loses value over time in the supply chain: in the critical time period between picking and cooling ( $t_0$  to  $t_1$  in Figure 4), product loses value at a rapid, exponential rate and the supply chain must be *responsive*. In the interval post-cooling ( $t_1$  to  $t_2$  in Figure 4), the product’s value declines at a much slower rate and the supply chain can be designed for cost *efficiency*.



In the analysis that follows, we demonstrate that design decisions for the responsive and efficient segments of the chain are only weakly linked, and the problem effectively separates into the design of each segment. We first develop an expression for minimizing cost in the responsive segment of the chain (from harvest to cooling), and then link this model to the design of the efficient segment of the chain.

### 3.1 Modeling the Responsive Segment of the Chain

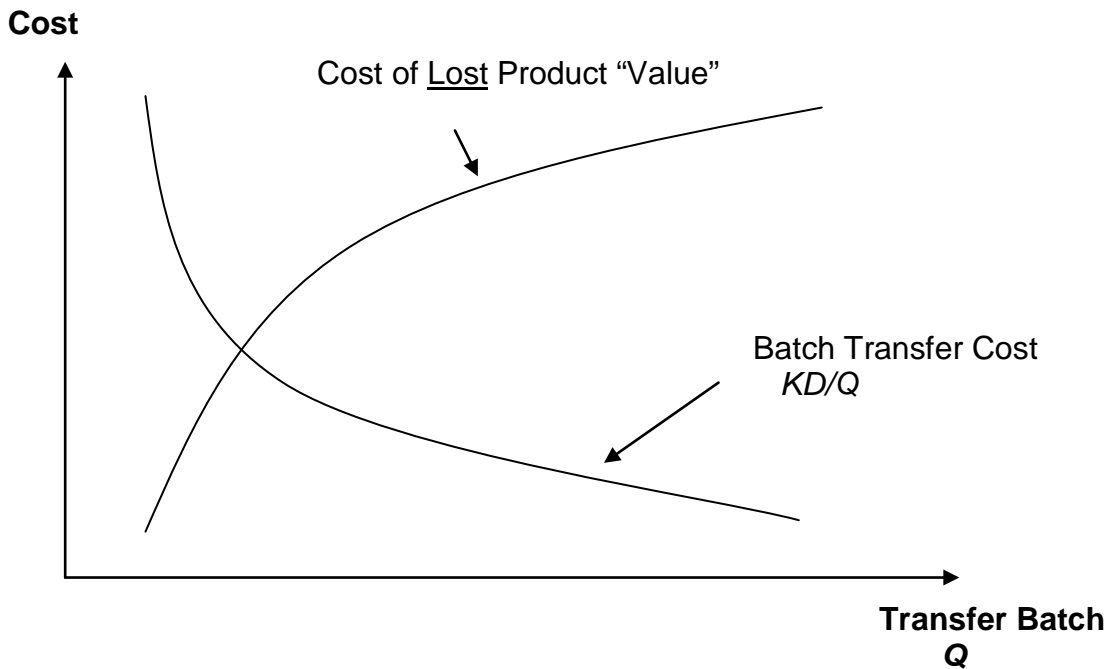
The total cost between picking and cooling can be modeled as an economic batch production model in which the key decision variables are the size of the batch of product to be transferred for cooling and the picking rate. Since loss in product value is well-fit by an exponential decay function, we assume a unit of product has value  $V$  at time of picking and degrades according to a function  $Ve^{-\alpha t}$ , where  $t$  denotes the time the unit is held at “field heat” and the decay parameter  $\alpha$  depends on both the product and the temperature (as was shown in Figure 3). Table 1 displays the observed  $\alpha$  values at various temperatures for melons and sweet corn (Suslow, Cantwell and Mitchell 2002; Appleman and Arthur 1919).

**Table 1**  
**Rate of Exponential Decay in Product Value**

Field Temp, °C.	Melons	Sweet Corn
0	0.001	0.005
10	0.003	0.015
20	0.006	0.027
30	0.030	0.130

Figure 5 is a schematic depicting the tradeoff facing the grower and distributor in the selection of the optimal transfer batch size,  $Q$ . The loss in product value is a concave increasing function of  $Q$ , and the cost of transferring batches of product to the cooling facility involves a fixed transfer cost that is analogous to the setup cost in a conventional lot-sizing problem.

**Figure 5**  
**Transfer Batch Cost Tradeoff for Perishable Products**



We assume that the unit of analysis for product is a *carton*; individual units of product can vary significantly in size and cartons are the standard transfer quantity. We introduce the following additional notation: let

$D$  = total # of cartons picked over the harvest period;

$Q$  = transfer batch size in cartons;

$V$  = maximum value of a carton of product at time  $t=0$ ;

$p$  = picking rate (cartons per hour);

$\alpha$  = deterioration rate in value of product per hour;

$K$  = batch transfer cost in dollars (assumed to be independent of the lot size);

$t_r$  = transfer time (in hrs) from field to cooling shed.

We assume continuous time by eliminating from consideration time intervals when picking does not take place (there is no loss in product value for product remaining “on the vine” overnight). Then the harvest period is of duration  $D/p$ , during which  $D/Q$  batches of product are picked. We assume that the total field harvest  $D$  and demand are equivalent and that  $D$  is determined exogenously. The decisions of interest are the batch size  $Q$  and picking rate  $p$  that minimize the total cost over the harvest period.

To construct the cost function, consider the  $q$ th unit picked in a batch  $Q$ . The  $q$ th unit is held in the field for a time  $t = (Q - q) / p$  plus a fixed transfer time  $t_r$  to move the batch to the cooling shed. The loss in value for the  $q$ th unit equals  $V \left[ 1 - e^{-\alpha(Q-q)/p} e^{-\alpha t_r} \right]$ . Define  $\tau_r = e^{-\alpha t_r}$ , and then the loss in value of a batch of size  $Q$  can be expressed as

$$QV - \tau_r \int_0^Q V e^{-\alpha(Q-q)/p} dq = QV - (p\tau_r V / \alpha)(1 - e^{-\alpha Q/p}) \quad (1)$$

The total cost per harvest period is simply the sum of the transfer costs  $KD/Q$ , the cost in “loss in value” per batch incurred  $D/Q$  times, and a picking cost. The total picking costs are closely approximated by a scalar multiple of demand,  $cD$ . This cost is independent of  $Q$  and  $p$  because doubling the picking rate would be accomplished by doubling the number of workers with virtually no change in the total cost of picking  $D$  cartons. This yields the following expression for total cost during the responsive segment of the chain:

$$TC(Q, p) = KD / Q + DV - (D / Q)(p\tau_r V / \alpha)(1 - e^{-\alpha Q/p}) + cD . \quad (2)$$

Equation (2) is structurally similar to the traditional economic order quantity (EOQ)

problem: the sum of a setup cost term ( $KD/Q$ ) and an expression that captures the loss in value while product is held in stock. We omit a traditional inventory carrying cost from the total cost expression because, given the short time interval (hours), the inventory carrying cost as a function of the batch size  $Q$  is negligible. However, including such a cost in the model would be trivial.

### 3.2 Modeling the Efficient Segment of the Supply Chain

We now complete the total cost model for the entire supply chain from harvest to retailer by incorporating the costs of transferring the product from cooling shed to retailer. Once the “cold chain” has been established, the product will remain stable for two to three weeks and will lose value at a much slower exponential rate  $\bar{V}e^{-\beta t}$ , where  $\beta \ll \alpha$  and  $\bar{V}$  = value of a unit at the time the cold chain is established.

The choices of transportation mode or carrier in the efficient segment of the chain are typically made from a small, finite set of size  $n$ ; there is not a continuum of cost/time choices. The cost and time to transport the product are essentially determined by the mode of transportation. Hence, we simply assume that there are  $n$  possible logistics choices. To incorporate these choices into a total cost expression for the supply chain design, let

$j$  = the transportation mode  $j$  ( $=1, \dots, n$ );  
 $t_j$  = transportation time for mode  $j$ ;  
 $C_j$  = cost of transportation mode  $j$ .



Since refrigerated truck is the most common option used for the transport of fresh produce, our model allows for the possibility of alternative truck carriers with different time and cost profiles, each identified as a different mode  $j$ .

To include the loss in value over the “efficient” segment of the chain, we assume that the time *each* carton spends in this segment is  $t_j$ . That is, any small cost differences in transportation from cooling to retailer due to batching in truck loading are ignored. Including the loss in value over this segment of the chain and the transport cost, we define  $\tau_j = e^{-\beta t_j}$  and modify (2) to obtain the following total cost expression:

$$TC(Q, p, j) = KD/Q + DV - (D/Q)(p\tau_j\tau_r V/\alpha)(1 - e^{-\alpha Q/p}) + cD + C_j. \quad (3)$$

Since demand is exogenous, expression (3) implies that the minimization of  $TC$  is independent of the value of  $D$  and is equivalent to the following:

$$\min TC(Q, p, j) = K/Q - (1/Q)(p\tau_j\tau_r V/\alpha)(1 - e^{-\alpha Q/p}) + C_j \quad \text{subject to } Q, p \geq 0. \quad (4)$$

### 3.3 Optimizing the Supply Chain Design

For each  $j$ , the optimal transfer batch  $Q$  and picking rate  $p$  are independent of the value of  $C_j$  and the only interaction between the two decisions is captured in the factor  $\tau_j$ .

However, because  $\beta$  tends to fall between 0.01-0.02 per day,  $\tau_j \geq 0.9$ , and the interaction is minimal. The transportation choice  $j$  has little effect on the decisions  $(Q, p)$  made in the responsive segment of the chain. With only a finite set of transportation choices, it is feasible to evaluate (4) for each  $j$  to determine the optimal design for both segments of the chain.

For a given  $j$ , the minimization of total cost in the supply chain is equivalent to the following:

$$\min TC(Q, p, j) = (1/Q) \left( K - (p\tau_j\tau_r V / \alpha) \right) (1 - e^{-\alpha Q/p}) \text{ subject to } Q, p \geq 0 \quad (5)$$

We show in Appendix 1 that for a given  $p$  the optimal  $Q$  satisfies the following expression:

$$Q = \left( \frac{p}{\alpha} - \frac{K}{\tau_j\tau_r V} \right) e^{\alpha Q/p} - \frac{p}{\alpha} \quad (6)$$

This expression has a unique solution that can be found by using a spreadsheet Solver routine. We further show in Appendix 1, Proposition 1.2 that the following lower bound, reminiscent of the classical EOQ formula, provides a good approximation to the optimal

$$\text{value: } Q \geq \sqrt{\frac{2pK}{\alpha\tau_j\tau_r V}}.$$

However, the joint minimization of  $TC(Q, p)$  does not have a finite solution. In Appendix 2 we show that although  $TC(Q, p)$  is convex in  $p$  for any value of  $Q$ ,

$$\frac{\partial TC(Q, p)}{\partial p} < 0 \text{ and } \lim_{p, Q \rightarrow \infty} TC(Q, p) = 0. \text{ That is, } TC(Q, p) \text{ is non-increasing in } p \text{ and the}$$

functions tends to zero asymptotically as  $p, Q \rightarrow \infty$ .

Although  $TC(Q, p)$  has no finite solution, in practice the picking rate is constrained by the physical limitations of the number of workers that can pick efficiently in coordination with a truck moving through the fields. For any batch size  $Q$ , if we denote the upper limit on the efficient picking rate as  $\bar{p}$ , then the optimal solution to (5) subject to  $p \leq \bar{p}$  is  $p = \bar{p}$ , and  $Q = \left( \frac{\bar{p}}{\alpha} - \frac{K}{\tau_j\tau_r V} \right) e^{\alpha Q/\bar{p}} - \frac{\bar{p}}{\alpha}$ .

### 3.4 Example: Applying the Model in the Responsive and Efficient Segments

We describe an example for the harvesting of canteloupes in Central California to illustrate how the model can be used to determine optimal harvesting strategy and the sensitivity of the solution to problem parameters. Using University of California agricultural data for melon values and our own field research for representative parameter values, we have the following inputs:  $V$ , the value of a carton of melons at time of picking, = \$7.00. At a field temperature of 30 °C,  $\alpha = 0.03$ . The maximum picking rate  $p = 60$  cartons per hour. The batch transfer transfer time,  $t_r$ , is 0.5 hours and with cost,  $K$ , of \$75. In the efficient segment of the chain,  $t_j = 5$  days,  $\beta = 0.02$  per day, and  $\tau_j = 0.91$ .

Using equation (6) we find that the optimal transfer batch size from field to cooling shed equals 227 cartons. To see that the time in the efficient segment of the chain has little effect on the optimal batch size, if we choose the batch transfer size based only on the total cost over the responsive segment (set  $\tau_j = 1$ ), then the optimal transfer batch size is reduced slightly to 217 cartons . In either case, the cost minimizing strategy is to transfer a batch to cooling about once every 3 ½ hours.

To examine the effect of the transportation mode, we observe that doubling  $t_j$  to 10 days for transportation mode  $j$  only increases the optimal  $Q$  value to 239. For field managers, the appropriate decision is still to transport product to the cooling shed approximately every 3-4 hours (at a 60 carton/hr picking rate). The solution is quite robust with respect to the choice of transportation mode, and the decisions made in the

efficient and responsive chain can be decoupled without significant deviation from optimality.

The optimal transfer batch size is sensitive to the decay rate  $\alpha$ , a value that varies with harvest temperature (and with produce type). Figure 6 displays optimal values of  $Q$  for our example over a range of  $\alpha$  values. When the deterioration rate is as low as  $\alpha = 0.01$  (corresponding to a field temperature of about 21 °C), the optimal batch quantity for a single picking team is about 60% of a full trailer quantity. The deterioration rate would need to be as low as .005 to justify transferring a full trailer batch of 590 cartons.

**Figure 6**  
**Optimal Transfer Batch Size for Melon Example**

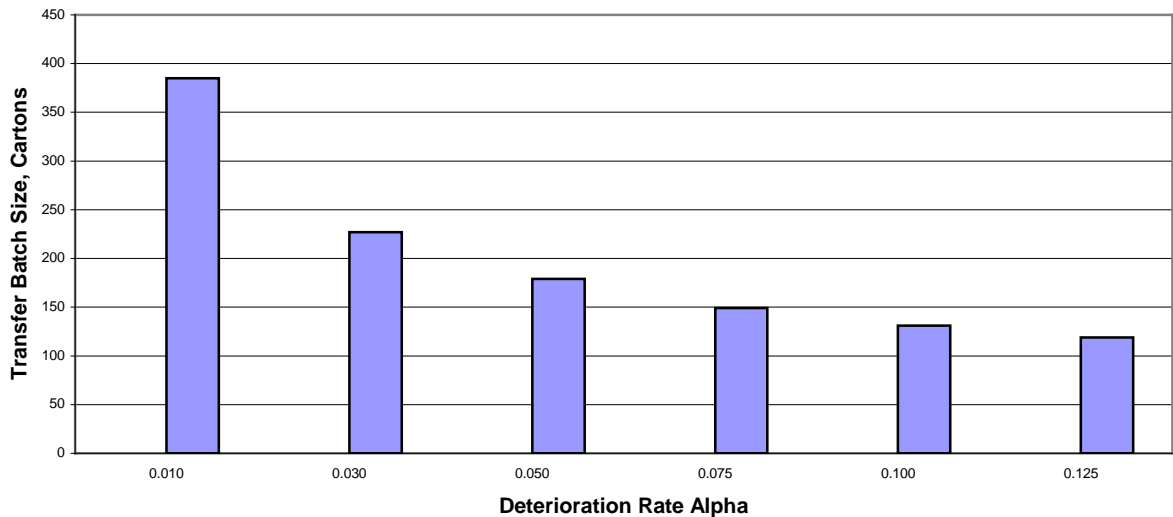
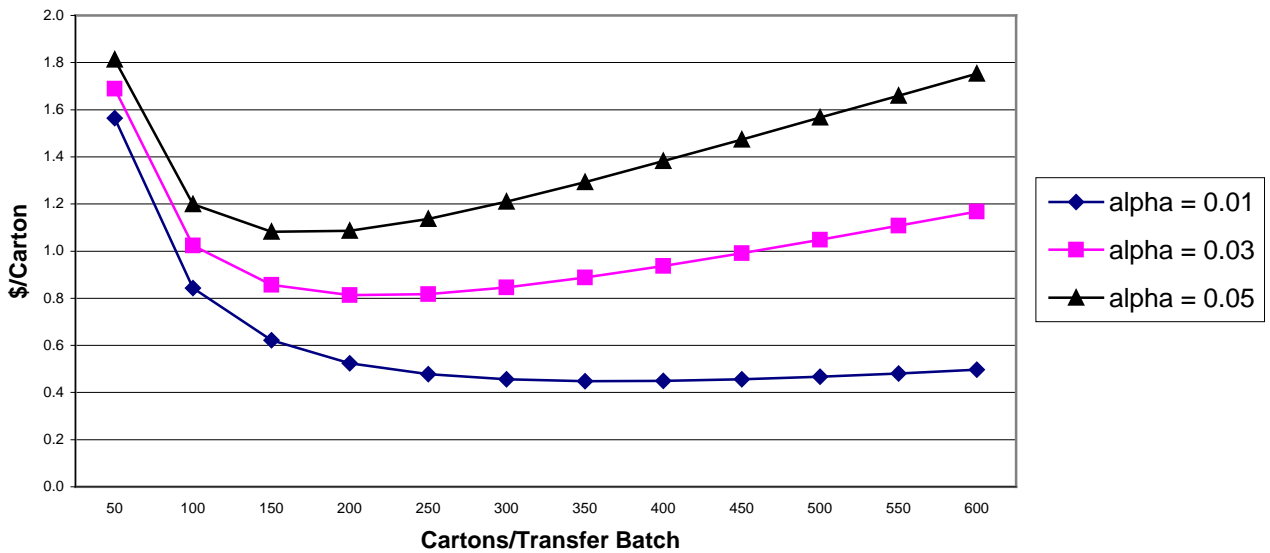


Figure 7 indicates how the total cost per carton is affected by the choice of the transfer batch size (at different values of  $\alpha$ ). The shapes of the total cost functions are similar to those for the traditional EOQ model: that is, the total cost is relatively insensitive to the choice of transfer batch size, when it is near the optimum. We observe, however, that as  $\alpha$  increases, the total cost becomes more sensitive to the choice of  $Q$ .

When  $\alpha$  is small, filling a truck completely with 600 cartons incurs a relatively small cost penalty. For  $\alpha = 0.03$ , the penalty is only about \$.40 per carton or \$240 for a full truckload. For  $\alpha = 0.01$ , the penalty is only \$30 for the full truckload. So the cost effect of filling a truck is relatively small for very low deterioration rates.

**Figure 7**  
**Total Cost per Carton vs. Transfer Batch Size**



Because the product deteriorates at a much slower rate after the “cold chain” is established, the choice of transportation mode  $j$  for the efficient segment of the chain is insensitive to the shipment time. To evaluate alternative modes of transport, the marginal value of time for the product may be used to impute the cost of an additional day of shipping time. To compute the marginal cost in lost product value of an additional day of shipping time, we take the partial derivative with respect to  $t_j$  of  $TC(Q, p, j)$ , as given in (3), yielding

$$\frac{\partial TC(Q, p, j)}{\partial t_j} = (\beta \tau_j) \left( \frac{D}{Q} \right) (p \tau_r V / \alpha) (1 - e^{-\alpha Q/p}) . \quad (7)$$

To calculate the marginal cost of an additional day of transportation time, we assume a six week harvest season, picking for eight hours per day, giving  $D = 20,200$  cartons of melons. Using (7) and our example data, the incremental lost product value of an additional day of transportation time is \$90. On a per unit basis, this is \$0.004, or less than a half cent per carton. Given that the cost in lost product value of an additional day in shipping is so small, the choice of shipping mode should be based primarily on reliability (maintaining the cold chain) and cost of shipment.

#### **4. Summary and Conclusions**

This paper examines a supply chain design problem for fresh produce, an example of a perishable product whose value declines exponentially post-production and can then be stabilized. By using the marginal cost of time for a product to develop a supply chain strategy, significant differences emerge between conventional supply chain strategies and those needed for perishable products. The supply chain for melons and sweet corn separates into two essentially independent segments: a “responsive” segment in which product deterioration rates are high and an “efficient” segment with lower deterioration rates.

An important result of this paper is that the decisions in each segment of the supply chain do not need to be coordinated to achieve supply chain optimization. The loose linkage between the responsive chain segment and the efficient segment means that each can be “designed” without a major effect on the other, or the overall quality of the product. By managing the process from picking through cooling, growers can maximize product value in the responsive segment of the chain by implementing optimal transfer

batch sizes. Shipping decisions can be based on cost efficiency, subject to the constraint that the “cold chain” is maintained throughout. The quantity shipped can, of course, be a much larger number than the transfer batch size,  $Q$ , in the responsive segment.

Although we have specifically modeled the supply chain for melons and corn, we note that our model also applies with minor modification to other fresh produce products that mature in the field and reach their peak value at time of harvest. Other products, notably flowers and seafood, have time-value patterns in the supply chain that are similar to melons and so our general results about supply chain strategy also apply to these perishable products. For perishable products whose loss in value cannot be stabilized, but continue to lose value at an exponential (or linear) rate, the model we develop for the responsive segment of the chain can be used for supply chain optimization.

This study introduces the concept of the marginal cost of time for a product as a tool to analyze supply chain strategy. We have begun to explore extensions of this concept to other product classes with different cost/time profiles. For example, other types of fresh produce, such as tomatoes and bananas, are often picked before maturity and allowed to ripen to their peak quality (and value) post-harvest. Designing a supply chain for this type of product poses additional interesting questions about the timing of production (or harvesting), managing the time interval while the product ripens to its peak value, and preserving the product value throughout the rest of the chain. The development of a supply chain strategy for such products with more complex time-value profiles is an interesting future research topic.

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### Appendix 1: Minimizing $TC(Q, p)$ and a Lower Bound on Optimal Value of $Q$

**Proposition 1.1:** For a given picking rate  $p (>0)$ , the function  $TC(Q, p)$  :

(1) is unimodal in  $Q$ ;

(2) has a unique minimum  $Q = \left( \frac{p}{\alpha} - \frac{K}{\tau_j \tau_r V} \right) e^{\alpha Q/p} - \frac{p}{\alpha}$ .

Proof: First observe that the cost expression

$TC(Q, p) = (1/Q) \left[ K - (p\tau_j \tau_r V / \alpha) (1 - e^{-\alpha Q/p}) \right]$  is not necessarily convex in  $Q$  because it is the sum of a convex function  $K/Q$  and an expression that is concave decreasing in  $Q$ . To find a local minimum for this function, we take

$$\frac{\partial TC(Q, p)}{\partial Q} = (-1/Q^2) \left[ K - (p\tau_j \tau_r V / \alpha) (1 - e^{-\alpha Q/p}) \right] - (\tau_j \tau_r V / Q) e^{-\alpha Q/p}.$$

Setting  $\frac{\partial TC(Q, p)}{\partial Q} = 0$ , we find that

$$Q = \left( \frac{p}{\alpha} - \frac{K}{\tau_j \tau_r V} \right) e^{\alpha Q/p} - \frac{p}{\alpha}. \quad (A1)$$

However, the second partial derivative with respect to  $Q$  is not necessarily non-negative:

$$\frac{\partial^2 TC(Q, p)}{\partial Q^2} = \frac{2}{Q^3} \left[ K - Q\tau_j \tau_r V e^{-\alpha Q/p} \right] + \left( \frac{2\tau_j \tau_r V}{Q^2} \right) e^{-\alpha Q/p} + \frac{\tau_j \tau_r V \alpha}{pQ} e^{-\alpha Q/p} \quad (A2)$$

can take on negative values for some (rare) combinations of  $Q$  and  $K$ .

Although not necessarily convex,  $TC(Q, p)$  is unimodal. To show this, we let  $Q = Q^*$  denote the solution to (A1) and show that  $Q^*$  is also the global minimum of  $TC(Q, p)$ .

We observe that (A1)  $\Rightarrow K = \frac{\tau_j \tau_r V p}{\alpha} (1 - e^{-\alpha Q^*/p}) - \tau_j \tau_r V Q e^{-\alpha Q^*/p}$ , and substituting for  $K$  in (A2), we have

$$\begin{aligned} \left. \frac{\partial^2 TC(Q, p)}{\partial Q^2} \right|_{Q=Q^*} &= \frac{2}{(Q^*)^3} [-\tau_j \tau_r V Q e^{-\alpha Q^*/p}] + \left( \frac{2\tau_j \tau_r V}{(Q^*)^2} \right) e^{-\alpha Q^*/p} + \frac{\tau_j \tau_r V \alpha}{p Q^*} e^{-\alpha Q^*/p} \\ &= \frac{\tau_j \tau_r V \alpha}{p Q^*} e^{-\alpha Q^*/p} > 0. \end{aligned}$$

Therefore, when  $\frac{\partial TC(Q, p)}{\partial Q} = 0$ , the second partial derivative is positive, and we conclude that the first partial derivative changes sign at most once; the solution to (A1) is a global minimum.

*Deriving a Lower Bound for the Optimal Value of  $Q$*

**Proposition 1.2:** When  $\alpha p / Q \ll 1$ , we have the following lower bound on  $Q^*$ , the value of  $Q$  that minimizes  $TC(Q, p)$ .  $Q^* \geq \sqrt{\frac{2pK}{\alpha \tau_j \tau_r V}}$ .

Proof: From (A1),  $Q^* = \left( \frac{p}{\alpha} - \frac{K}{\tau_j \tau_r V} \right) e^{\alpha Q^*/p} - \frac{p}{\alpha}$

or  $\left( 1 + \frac{\alpha Q^*}{p} \right) e^{-\alpha Q^*/p} = 1 - \frac{\alpha K}{p \tau_j \tau_r V}$ .

Replacing  $e^{-\alpha Q^*/p}$  by its infinite series expansion and substituting gives the following:

$$(Q^*)^2 = \frac{2pK}{\alpha \tau_j \tau_r V} + \frac{2}{3} \left( \frac{\alpha}{p} \right) (Q^*)^3 - \frac{1}{4} \left( \frac{\alpha^2}{p^2} \right) (Q^*)^4 + \frac{1}{15} \left( \frac{\alpha^3}{p^3} \right) (Q^*)^5 - \dots$$

When  $\alpha p / Q^* \ll 1$ , the terms in the expansion diminish rapidly and we have that

$$Q^* \geq \sqrt{\frac{2pK}{\alpha \tau_j \tau_r V}}.$$

## Appendix 2

**Proposition 2.1:** For fixed  $Q$ ,  $TC(Q, p)$  is convex with respect to  $p$ .

Proof: Taking partial derivatives, we have

$$\frac{\partial TC(Q, p)}{\partial p} = -\frac{\tau_j \tau_r V}{\alpha Q} (1 - e^{-\alpha Q/p}) + \frac{\tau_j \tau_r V}{p} e^{-\alpha Q/p}$$

$$\text{and } \frac{\partial^2 TC(Q, p)}{\partial p^2} = \frac{\tau_j \tau_r V \alpha Q}{p^3} (e^{-\alpha Q/p}) \geq 0.$$

Therefore,  $TC(Q, p)$  is convex in  $p$ .

**Proposition 2.2:** For fixed  $Q$ ,  $TC(Q, p)$  is non-increasing in  $p$  and  $\lim_{p, Q \rightarrow \infty} TC(Q, p) = 0$ .

Proof: Setting  $\frac{\partial TC(Q, p)}{\partial p} = 0$  and solving for  $p$  yields the following:

$$p = \alpha Q \frac{e^{-\alpha Q/p}}{(1 - e^{-\alpha Q/p})}. \quad (\text{A3})$$

Let  $\alpha Q / p = x$ , then (A3) can be rewritten as  $x = e^x - 1$ , which has a unique solution,  $x = 0$  and no finite value of  $p$  satisfies expression (A3). Given the convexity of  $TC(Q, p)$ , this implies that  $TC(Q, p)$  is non-increasing in  $p$  and tends to 0 as  $Q, p \uparrow \infty$ .