# Perishable Food Supply Chain Networks with Labor in the Covid-19 Pandemic

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**Abstract:**

The Covid-19 pandemic is a major healthcare disaster that has fundamentally transformed our daily lives and the operations of governments, businesses, healthcare operations, and educational institutions. It has elevated and expanded the role of essential workers, not only in healthcare but also in the food industry. The food industry has undergone major disruptions in the pandemic for reasons including compromised labor resources. In this paper, we develop a supply chain generalized network optimization framework focused on perishable food. The model explicitly includes labor availability associated with the network economic activities of production, transportation, storage, and distribution in order to quantify the impacts of associated disruptions due to illnesses, physical/social distancing requirements, and decreases in labor productivity. Theoretical results are presented along with a series of numerical examples on a fresh produce product with quantification of a spectrum of pandemic-induced disruptions on product flows, demands, prices, and the profits of the food firm. We also show that including more direct demand markets for fresh produce can yield gains for the firm.

**Keywords:** perishable food supply chains, labor resources, network optimization, disruptions, pandemic

## 1. Introduction

Perishable food products including fresh produce, dairy items, meat, and fish are essential for health and well-being. The associated nutrition in such products helps to sustain life and supports a strong immune system and response to illnesses. During the Covid-19 pandemic, these vital food supply chains have been critically stressed for several reasons, including that workers are becoming ill from the SARS-Cov-2 coronavirus with some tragically succumbing to the disease and with others reluctant to work because of fear of contagion (Bjattarai and Reiley (2020)). The coronavirus has also added risk of contagion for workers engaged in supply chain network activities of production, transportation, processing, storage, and distribution since physical/social distancing may be challenging and, yet, essential to the mitigation of the spread of the virus.

Most visible, to-date, as of June 2020, has been the immense negative impact of the pandemic on meat supply chains in the United States (see Hirtzer and Skerrit (2020) and Scheiber and Corkery (2020)). Many of the meat supply chains for pork, beef, and chicken utilize processing plants belonging to large agribusinesses located in different states (Little (2020), Rosane (2020), Reiley (2020)). Close to two dozen of such plants have had to shut down due to illnesses of the workers in March and April 2020, impacting farmers and consumers alike (Corkery and Yaffe-Bellany (2020)). At a time when there is growing food insecurity due to loss of jobs (Morath (2020)) as a consequence of the pandemic, farmers have even resorted to culling their animals when they cannot be processed (Polansek and Huffstutter (2020)). Some meat processing plants, after shutting down, have undergone disinfection of their facilities and the workers have quarantined themselves for fourteen days, causing further delays and uncertainty as to the availability of fresh meat for consumers (Pitt (2020)).

Also, with schools, restaurants, and hotels closed, the demand not only for meat but also for fresh produce as well as dairy has changed (Schrotenboer (2020)). Some potato farmers, unable to get their produce processed, are resorting to discarding their ripe vegetables (Associated Press (2020)). This dumping of food creates a huge amount of waste, results in a reduction to the farmer's incomes, and also diminishes the amount available for consumers (see, e.g., Wootson Jr. (2020)). Dairy farmers also got hit early in the pandemic and many have had to discard the milk from their cows due to processing (Huffstutter (2020)). There have also been disruptions associated with freight service provision, with truckers fearing contracting the coronavirus (CBSSacramento (2020)).

Furthermore, with summer approaching and the harvesting of many fresh fruits and vegetables on the horizon in the United States, migrant labor may be in short supply for picking the harvest because of reluctance to risk contracting the coronavirus (Shoichet (2020) and Nickel and Walljasper (2020)). Clearly, we are seeing that labor is a crucial resource in perishable food supply chain networks, now compromised because of labor availability issues. Agribusiness firms and even farmers are starting to reevaluate their food supply chains even investigating possible new distribution channels and demand markets and this is also a global issue (see Cullen (2020)).

Interestingly, although economists have tackled the use of factors of production; notably, capital and labor, in production functions (see see Mishra (2007) and the references therein), the explicit incorporation of labor into a complete supply chain network for perishable products has not been thoroughly investigated. This is an important area of research since only when a system-wide perspective is taken can one identify the impacts of labor availability and disruptions during a pandemic on profits, costs, product waste, and consumer prices. As a side effect, there is also a quality issue since delays in a cold chain may impact the quality of the perishable product (cf. Yu and Nagurney (2013), Besik and Nagurney (2017), Nagurney and Li (2016), Nagurney, Besik, and Yu (2018)). Indeed, as noted in Yu and Nagurney (2013), food supply chains are different from other supply chains in that there is a continuous and significant change in the quality of the food products as they move through the pathways of entire supply chain to points of demand and consumption. Hence, the quality of food products decreases over time, even under the best cold chain processes (see Sloof, Tijskens, and Wilkinson (1996), Zhang, Habenicht, and Spiess (2003), Rong, Akkerman, and Grunow (2011)).

Ahumada and Villalobos (2009) present a review of agricultural supply chains with Higgins et al. (2010) focusing on practice and network analysis. The review of Bjorndal et al. (2012) details operations research applications that include agriculture and fisheries. The meat industry, and, in particular, meat processing plant activities have garnered attention from operations researchers from the modeling perspective dating to 1990 (Whitaker and Cammel (1990)). For example, Albornoz et al. (2015) developed an elegant mixed integer programming model focusing on meat packing operations for pork at the operational level and included worker daily hours but emphasized that they did not handle distribution. Additional recent work identifying research gaps is that of Rodriguez, Pla, and Faulin (2014). The volume edited by Baourakis, Migdalas, and Pardalos (2004) contains a collection of articles on supply chains and finance, exemplifying a wide range of methodologies used as well as tools for risk management. Several articles therein are focused on food. Vlontzos and Pardalos (2017) describe data mining and optimisation issues in the food industry and note a wide range of successful case studies on fresh produce as well as processed foods. Nevertheless, a fundamental supply chain network optimization model for perishable food products that

(1). includes labor on all the supply chain network economic activities;

(2). can be utilized to quantify impacts of labor disruptions and

(3). can applied to different food products, with appropriate adaptations,

has not, heretofore, been constructed.

In this paper, we develop a generalized supply chain network optimization model for perishable food products with the inclusion of the critical resource of labor in the supply chain network economic activities. This work extends that of Yu and Nagurney (2013) to include labor and its associated levels of availability. Although the literature on supply chain network optimization is rich (cf. Geunes and Pardalos (2003), Nagurney (2006), Wu and Blackhurst (2009), Nagurney and Li (2016), and the references therein), it has not integrated labor into a rigorous mathematical framework for product perishability (cf. Nagurney et al. (2013)). Such an integration can provide valuable insights for the management and analysis of perishable food supply chains during the pandemic and even in times when the world is not faced with a global healthcare catastrophe. This work also adds to our understanding of complex phenomena associated with dynamics of disasters (see Kotsireas, Pardalos, and Nagurney (2016, 2018)). The contributions in this paper set the stage for research on other perishable product supply chains in which labor is essential and subject to disruptions as we are seeing during the Covid-19 pandemic.

This paper is organized as follows. In Section 2 we construct the perishable food supply chain network model with the inclusion of labor and provide the variational inequality formulation, along with the theoretical analysis. We then, in Section 3 propose an algorithm, which resolves the problem into closed form expression for the product flows on the supply chain network paths at each iteration, along with the Lagrange multipliers associated with the labor availability link capacities. The algorithm is applied to compute solutions to a series of numerical examples consisting of a fresh produce product. The numerical examples quantify the impacts of labor reductions, a decrease in labor productivity, and a freight service disruption on the food firm's optimal sales, profits, labor resources, as well as the consumer demand. We conclude with Section 4, in which we summarize our results and also present suggestions for future research.

## 2. The Perishable Food Supply Chain Network Models with Labor

We consider a single food firm, which depending upon the application can be a farm or even an agribusiness. We assume that a single perishable food product is produced (such as a meat or dairy product, fresh fruit or vegetable, etc.). The profit-maximizing food firm's supply chain network is depicted in Figure 1. We emphasize that this topology may be adapted/modified according to the specific application. We denote the topology by the graph $G = [N, L]$, where $N$ is the set of nodes and $L$ is the set of links.

The top node 1 in Figure 1 corresponds to the food firm and the bottom nodes: $w_1, \ldots, w_J$ correspond to the demand markets. The demand markets can be grocery stores, organizations (such as hospitals or even food banks), and/or direct consumers. We assume that there exists one directed path (or more) joining node 1 with each demand node. Note that the the supply chain network topology in Figure 1 has curved links to denote direct sales, which can even capture sales at the farm, farmers' markets, or sales direct to the other-noted demand markets above without going through storage and other shipment links. Different distribution channels are now of increasing importance to food firms because of the pandemic, as emphasized in the introduction.

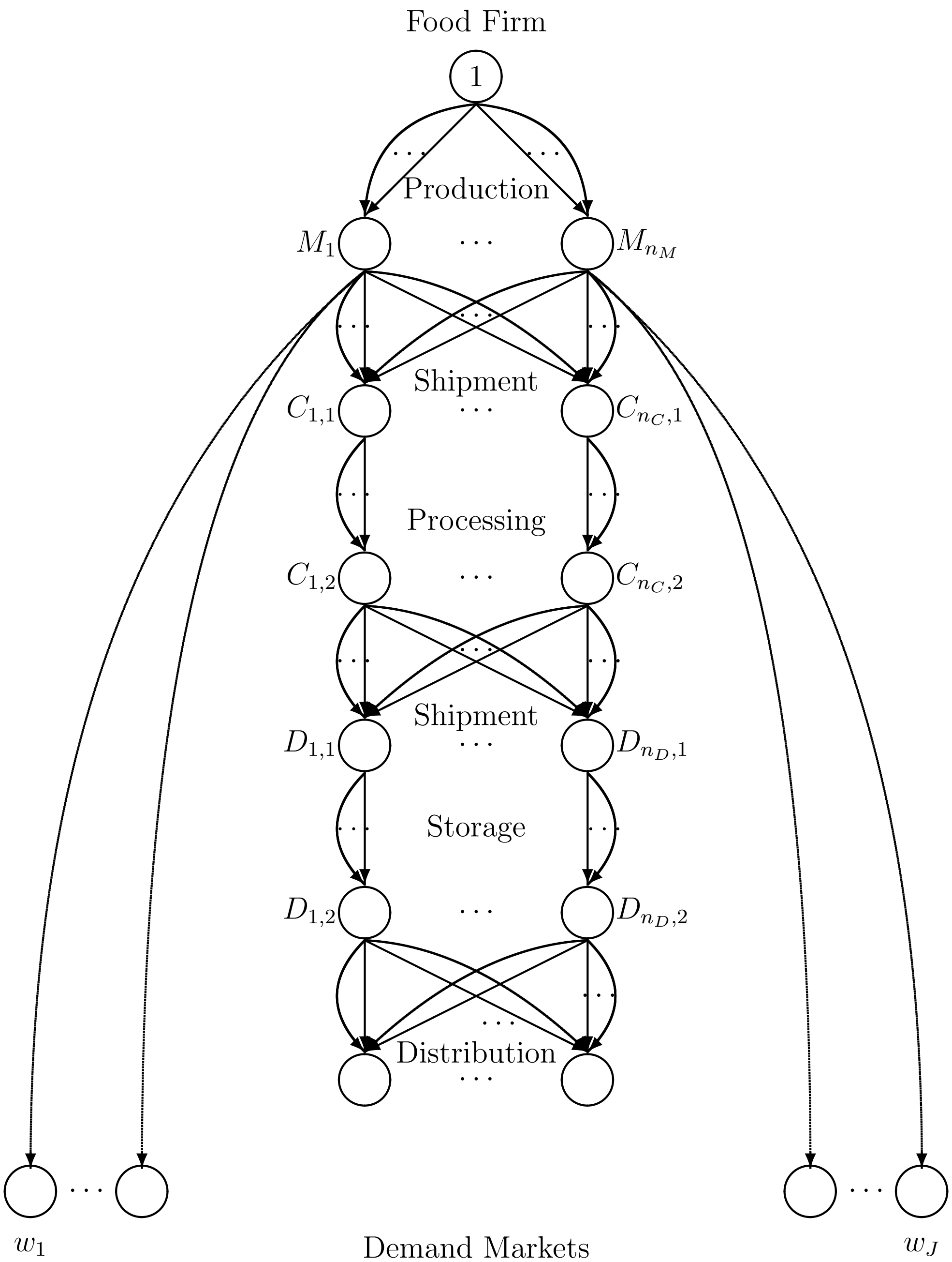


Figure 1: The Perishable Food Supply Chain Network Topology

As depicted in Figure 1, the food firm is considering $n_M$ production sites; $n_C$ processors, $n_D$ distribution centers, and must serve the $J$ demand markets. The top set of links connecting the top two tiers of nodes corresponds to the food production at each of the production sites of the firm. We allow for multiple possible links connecting node 1 with its production facilities, $M_1, \ldots, M_{n_M}$, to allow for different production technologies at different costs.

The second set of links in Figure 1 from the production site nodes is connected to the processors of the firm and are denoted by $C_{1,1}, \ldots, C_{n_C,1}$. These links correspond to the shipment links between the production sites and the processors. Different links represent different possible modes of transport. The third set of links connecting nodes $C_{1,1}, \ldots, C_{n_C,1}$ to $C_{1,2}, \ldots, C_{n_C,2}$, denotes the processing of the perishable food product.

The next set of nodes in Figure 1 represents the distribution centers, and, thus, the fourth set of links connecting the processor nodes to the distribution centers is the set of shipment links. The distribution nodes are denoted by $D_{1,1}, \ldots, D_{n_D,1}$. Here we also allow for multiple modes of transport. Note that faster ones may be more costly than slower ones, for example.

The fifth set of links in Figure 1 connects nodes $D_{1,1}, \ldots, D_{n_D,1}$ to $D_{1,2}, \ldots, D_{n_D,2}$, and corresponds to the storage links. Different technologies, at associated costs, may be available for the storage network economic activity.

The final group of links in Figure 1 connecting the two bottom tiers of the supply chain network corresponds to distribution links over which the perishable food product items are shipped from the distribution centers to the demand markets. As noted earlier, the curved links in Figure 1 joining the upstream production nodes with the direct demand market nodes capture the possibility of on-site production and processing and direct availability, with the latter representing demand market nodes located at the farms, or at farmers' markets, or transported directly to consumers or other demand points.

A path $p$ in the perishable food supply chain network joins node 1, which is the origin node, to a demand market node, which is a destination node. The paths are acyclic and consist of a sequence of links capturing the supply chain network activities associated with producing the perishable product and having it finally provided at the demand markets. Let $P_{w_j}$ denote the set of paths, which represent alternative associated possible supply chain network processes, joining the pair of nodes $(1, w_j)$. $P$ denotes the set of all paths joining node 1 to the demand market nodes. There are $n_P$ paths in the supply chain network and $n_L$ links. Denote a typical demand market node by $w$ and a typical link by $a$. The set of all pairs of origin and demand market nodes is denoted by $W$.

The notation for the model is given in Table 1. All vectors are assumed to be column vectors.

Table 1: Notation for the Perishable Food Supply Chain Network Models with Labor

| **Notation** | **Variables** |
|---|---|
| $x_p$ | the product flow on path $p$; we group all the path flows into the vector $x \in R_+^{n_P}$. |
| $f_a$ | the product flow on link $a$; we group all the link flows into the vector $f \in R_+^{n_L}$. |
| $l_a$ | the labor available for link $a$ activity, $\forall a \in L$. |
| $d_{w_j}$ | the demand for the product at demand market $w_j$; $j = 1, \ldots, J$; we group the demands into the vector $d \in R_+^J$. |
| **Notation** | **Parameters** |
| $\alpha_a$ | the throughput factor on link $a$, which lies in the range $(0, 1]$. |
| $\mu_p$ | the throughput on path $p$, where $\mu_p = \prod_{a \in p} \alpha_a$; $p \in P$. |
| $\beta_a$ | positive factor relating inputs of labor to out of product flow on link $a$, $\forall a \in L$. |
| $\bar{l}_a$ | the upper bound on the availability of labor on link $a$, $\forall a \in L$. |
| $\pi_a$ | the unit cost of labor at link $a$, $\forall a \in L$. |
| **Notation** | **Functions** |
| $\hat{z}_a(f_a)$ | the discarding cost associated with link $a$, $\forall a \in L$. |
| $\hat{c}_a(f)$ | the total cost associated with link $a$, excluding the labor and discarding costs, $\forall a \in L$. |
| $\rho_{w_j}(d)$ | the demand price for the product at demand market $w_j$; $j = 1, \ldots, J$. |

The path flows must be nonnegative, that is,

$$x_p \geq 0, \quad \forall p \in P. \tag{1}$$

We handle the perishability of the product through the use of arc multipliers in a generalized network framework. Associated with each arc is an implicit time duration for completion, which can depend on the labor availability and is incorporated in the multiplier $\alpha_a$ for each link $a$. Of course, in the best scenario, one would expect full labor availability and efficient processing resulting in lower food waste. Here, as argued in Yu and Nagurney (2013), the arc multipliers describe the decrease in quantity, which allows for the capture of the discarding of spoiled products along the pathways consisting of the supply chain links to the demand markets. Such an approach has origins in the work of Nahmias (1982) in studies on perishable inventory. For example, in the case of fresh produce items, such as fruits and vegetables, exponential time decay is often used. For further background on food science and food deterioration, we refer the interested reader to Thompson (2002) and Gustavsson et al. (2011).

Here we assume that the arc multiplier $\alpha_a$ on production links is identically equal to 1. We now recall the definition of arc path multipliers, which were introduced for food supply chains in Yu and Nagurney (2013). The multiplier, $\alpha_{ap}$, which is the product of the multipliers of the links on path $p$ that precede link $a$ in that path, is defined as:

$$\alpha_{ap} \equiv \begin{cases} \delta_{ap} \prod_{b \in \{a' < a\}_p} \alpha_b, & \text{if } \{a' < a\}_p \neq \emptyset, \\ \\ \delta_{ap}, & \text{if } \{a' < a\}_p = \emptyset, \end{cases} \tag{2}$$

where $\{a' < a\}_p$ denotes the set of the links preceding link $a$ in path $p$, and $\emptyset$ denotes the null set. In addition, $\delta_{ap}$ is defined as equal to 1 if link $a$ is contained in path $p$, and 0, otherwise. If link $a$ is not contained in path $p$, then $\alpha_{ap}$ is set to zero. Hence, the relationship between the link flow, $f_a$, and the path flows can be expressed as:

$$f_a = \sum_{p \in P} x_p \alpha_{ap}, \quad \forall a \in L. \tag{3}$$

We emphasize that the above types of multipliers have also been used in other perishable product supply chain models for pharmaceuticals by Masoumi, Yu, and Nagurney (2012) and for blood supply chains by Nagurney, Masoumi, and Yu (2012) and Nagurney and Dutta (2019).

In addition, here we consider the following relationship between link flows and labor:

$$f_a = \beta_a l_a, \quad \forall a \in L. \tag{4}$$

According to (4), the output on each link of product is a linear function of the labor input. This is a linear production function, according to economics (cf. Samuelson and Marks (2012)). Observe that with (4) we assume that the labor is applied/exerted with the product flow as at the beginning of the link $a$. However, what is left of $f_a$ as the flow traverses the link, $f'_a$, is $\alpha_a f_a$ (see Yu and Nagurney (2013)).

Since we make use of a discarding cost function $\hat{z}_a$, for each link, we notice that:

$$f_a - f'_a = (1 - \alpha_a) f_a, \quad \forall a \in L, \tag{5}$$

so we can write that

$$\hat{z}_a = \hat{z}_a(f_a), \quad \forall a \in L. \tag{6}$$

Also, the demand for the perishable food product at a demand market $w$ is equal to the sum of the final product flows at the demand market, that is,

$$\sum_{p \in P_w} x_p \mu_p = d_w, \quad \forall w \in W. \tag{7}$$

Finally, the labor utilized on a supply chain network link cannot exceed the amount of labor available for that link:

$$l_a \leq \bar{l}_a, \quad \forall a \in L. \tag{8}$$

The food firm seeks to maximize its profits, which is essential for its business sustainability. The objective function faced by the firm is, hence, the difference between the revenue denoted by the sum over all the demand markets of the price the consumers are willing to pay for the product at a demand market times the demand there minus the total costs consisting of the costs associated with the links (exclusive of the labor and discarding costs), the discarding costs, and the costs associated with labor on the links:

$$\text{Maximize} \sum_{w \in W} \rho_w(d) d_w - \Big(\sum_{a \in L} \hat{c}_a(f) + \hat{z}_a(f_a)\Big) - \sum_{a \in L} \pi_a l_a, \tag{9}$$

subject to constraints: (1), (3), (4), (7), and (8).

We assume here that the cost functions are convex and continuously differentiable and that the demand price function is monotone decreasing and continuously differentiable. In view of (3) and (7) we can re-define the cost and demand price functions in terms of path flows as follows: $\tilde{c}_a(x) \equiv \hat{c}_a(f)$, $\forall a \in L$; $\tilde{z}_a(x) \equiv \hat{z}_a(f_a)$, $\forall a \in L$; $\tilde{\rho}_w(x) \equiv \rho_w(d)$, $\forall w \in W$.

Furthermore, in view of (3), (4), and (7), we can express objective function (9) solely in terms of path flows by incorporating these constraints directly into the objective function. Hence, the objective function (9) now becomes the following in path flows:

$$\text{Maximize} \sum_{w \in W} \tilde{\rho}_w(x) \sum_{p \in P_w} \mu_p x_p - (\sum_{a \in L} \tilde{c}_a(x) + \sum_{a \in L} \tilde{z}_a(x)) - \sum_{a \in L} \frac{\pi_a}{\beta_a} \sum_{p \in P} x_p \alpha_{ap}. \tag{10}$$

Since (3), (4), and (7) are directly incorporated into the objective function (10), we still retain the nonnegativity assumption on the path flows (1), and constraint (8) becomes, in path flows:

$$\frac{\sum_{p \in P} x_p \alpha_{ap}}{\beta_a} \leq \bar{l}_a, \quad \forall a. \tag{11}$$

Under our assumptions, the objective function (10) is convex, and the underlying feasible set is closed and convex.

### 2.1 Variational Inequality Formulation

In this subsection, we provide the variational inequality (VI) formulation of the above perishable food product supply chain network optimization model with labor. The solution to the supply chain network optimization model with labor is guaranteed to exist since the feasible set is bounded due to capacities on the availability of labor on the supply chain network links and, hence, also, of the product flows. This result follows from the classical theory of variational inequalities (Kinderlehrer and Stampacchia (1980)).

The proof of the below formulation follows from the classical theory of variational inequalities (Kinderlehrer and Stampacchia (1980) and Nagurney (1999)) and the arguments as in Masoumi, Yu, and Nagurney (2012) (see also Nagurney, Masoumi, and Yu (2012)).

**Variational Inequality Formulation**

With the link labor constraint for each link $a$ given by (11) we associate the nonnegative Lagrange multiplier $\lambda_a$ and group these Lagrange multipliers into the vector $\lambda \in R^{n_L}_+$. We define the feasible set $K^1 \equiv \{(x,\lambda) \in R_+^{n_P+n_L}\}$. The solution to the perishable food product supply chain network optimization problem is equivalent to the solution of the VI: determine $(x^*,\lambda^*) \in K^1$ such that

$$\sum_{w\in W}\sum_{p\in P_w}\left[\frac{\partial \hat{C}_p(x^*)}{\partial x_p}+\frac{\partial \hat{Z}_p(x^*)}{\partial x_p}+\sum_{a\in L}\frac{\pi_a}{\beta_a}\alpha_{ap}-\hat{\rho}_w(x^*)\mu_p-\sum_{v\in W}\frac{\partial \hat{\rho}_v(x^*)}{\partial x_p}\sum_{q\in P_v}\mu_q x_q^*+\sum_{a\in L}\frac{\lambda_a^*}{\beta_a}\alpha_{ap}\right]$$

$$\times\left[x_p-x_p^*\right]+\sum_{a\in L}\left[\bar{l}_a-\frac{\sum_{p\in P}x_p^*\alpha_{ap}}{\beta_a}\right]\times[\lambda_a-\lambda_a^*]\geq 0, \quad \forall (x,\lambda)\in K^1, \tag{12}$$

where for each path $p \in P_w$, $\forall w \in W$:

$$\frac{\partial \hat{C}_p(x)}{\partial x_p}\equiv\sum_{a\in L}\sum_{b\in L}\frac{\partial \hat{c}_b(f)}{\partial f_a}\alpha_{ap}, \quad \frac{\partial \hat{Z}_p(x)}{\partial x_p}\equiv\sum_{a\in L}\sum_{b\in L}\frac{\partial \hat{z}_b(f)}{\partial f_a}\alpha_{ap}, \quad \frac{\partial \hat{\rho}_w(x)}{\partial x_p}\equiv\frac{\partial \rho_w(d)}{\partial d_w}\mu_p. \tag{13}$$

Variational inequality (12) is now put into standard form (cf. Nagurney (1999)): determine $X^* \in \mathcal{K}$ such that:

$$\langle F(X^*), X-X^*\rangle \geq 0, \quad \forall X \in \mathcal{K}. \tag{14}$$

where $\langle\cdot,\cdot\rangle$ denotes the inner product in $n$-dimensional Euclidean space.

Let $X \equiv (x,\lambda)$ and $F(X) \equiv (F_1(X), F_2(X))$ where

$$F_1(X)=\left[\frac{\partial \hat{C}_p(x)}{\partial x_p}+\frac{\partial \hat{Z}_p(x)}{\partial x_p}+\sum_{a\in L}\frac{\pi_a}{\beta_a}\alpha_{ap}\right.$$

$$\left.-\hat{\rho}_w(x)\mu_p-\sum_{v\in W}\frac{\partial \hat{\rho}_v(x)}{\partial x_p}\sum_{q\in P_v}\mu_q x_q+\sum_{a\in L}\frac{\lambda_a}{\beta_a}\alpha_{ap}; w\in W; p\in P_w\right],$$

$$F_2(X)\equiv\left[\bar{l}_a-\frac{\sum_{p\in P}x_p\alpha_{ap}}{\beta_a}; a\in L\right]. \tag{15}$$

## 3. Computational Procedure and Numerical Examples

The algorithm that we apply in this section to compute solutions to numerical examples, whose solutions satisfy VI (12), is the modified projection method of Korpelevich (1977). Each of the algorithm's two fundamental steps at an iteration result in closed form expressions for the computation of the path flows as well as the Lagrange multipliers associated with the link labor capacities. Hence, the algorithm is relatively easy to implement, even in the case of a generalized network as in our perishable food product supply chain network optimization model.

Specifically, steps of the modified projection method are given below, with $\tau$ denoting an iteration counter:

**The Modified Projection Method**

**Step 0: Initialization**

Initialize with $X^0 \in \mathcal{K}$. Set the iteration counter $\tau := 1$ and let $\eta$ be a scalar such that $0 < \eta \leq \frac{1}{\mathcal{L}}$, where $\mathcal{L}$ is the Lipschitz constant (cf. (19) below).

**Step 1: Computation**

Compute $\bar{X}^\tau$ by solving the variational inequality subproblem:

$$\langle \bar{X}^\tau + \eta F(X^{\tau-1}) - X^{\tau-1}, X - \bar{X}^\tau \rangle \geq 0, \quad \forall X \in \mathcal{K}. \tag{16}$$

**Step 2: Adaptation**

Compute $X^\tau$ by solving the variational inequality subproblem:

$$\langle X^\tau + \eta F(\bar{X}^\tau) - X^{\tau-1}, X - X^\tau \rangle \geq 0, \quad \forall X \in \mathcal{K}. \tag{17}$$

**Step 3: Convergence Verification**

If $|X^\tau - X^{\tau-1}| \leq \epsilon$, with $\epsilon > 0$, a pre-specified tolerance, then stop; otherwise, set $\tau := \tau + 1$ and go to Step 1.

The modified projection method is guaranteed to converge to a solution of VI (13) provided that the function $F(X)$ is monotone and Lipschitz continuous (and that a solution exists). We now recall the definitions of these properties. The function $F(X)$ is said to be monotone, if

$$\langle F(X^1) - F(X^2), X^1 - X^2 \rangle \geq 0, \quad \forall X^1, X^2 \in \mathcal{K}, \tag{18}$$

and the function $F(X)$ is Lipschitz continuous, if there exists a constant $\mathcal{L} > 0$, known as the Lipschitz constant, such that

$$\|F(X^1) - F(X^2)\| \leq \mathcal{L}\|X^1 - X^2\|, \quad \forall X^1, X^2 \in \mathcal{K}. \tag{19}$$

These conditions we expect to hold in many reasonable applications of our model.

### 3.1 Numerical Examples

The modified projection method was implemented in FORTRAN and a Linux system at the University of Massachusetts Amherst used for the computation of solutions to the subsequent numerical examples. The numerical examples are inspired by a fresh produce application, specifically, that of cantaloupes, which are a rich source of nutrients. Cantaloupes consumed in the United States are produced in California and in Mexico and parts of Central America. Here we focus on production in the United States and consider a food firm with two production sites, a single processor, two distribution centers, and two demand markets, all of which are located in the Unites States. The numerical examples, hence, have the supply chain network topology depicted in Figure 2, except where noted. The links are labeled numerically.

As noted in the introduction, perishable food products deteriorate over time even under the best conditions. Here, as in Yu and Nagurney (2013), from which our dataset is adapted, we assume that the temperature and other environmental conditions associated with each post-production activity/link are given and fixed. Hence, as in Nahmias (1982), each perishable food unit has a probability of $e^{-\gamma t}$ to survive another $t$ units of time, where $\gamma$ is the decay rate, which is given and fixed. Let $N_0$ denote the quantity at the beginning of the time interval (link). Then, the quantity surviving at the end of the time interval, which is implicit for each link in our supply chain network, follows a binomial distribution with parameters $n = N_0$ and probability$= e^{-\gamma t}$. Consequently, the expected quantity surviving at the end of the time interval (specific link), denoted by $N(t)$, can be expressed as:

$$N(t) = N_0 e^{-\gamma t}. \tag{19}$$

Hence, in our application to cantaloupes, the throughput factor $\alpha_a$ for a post-production

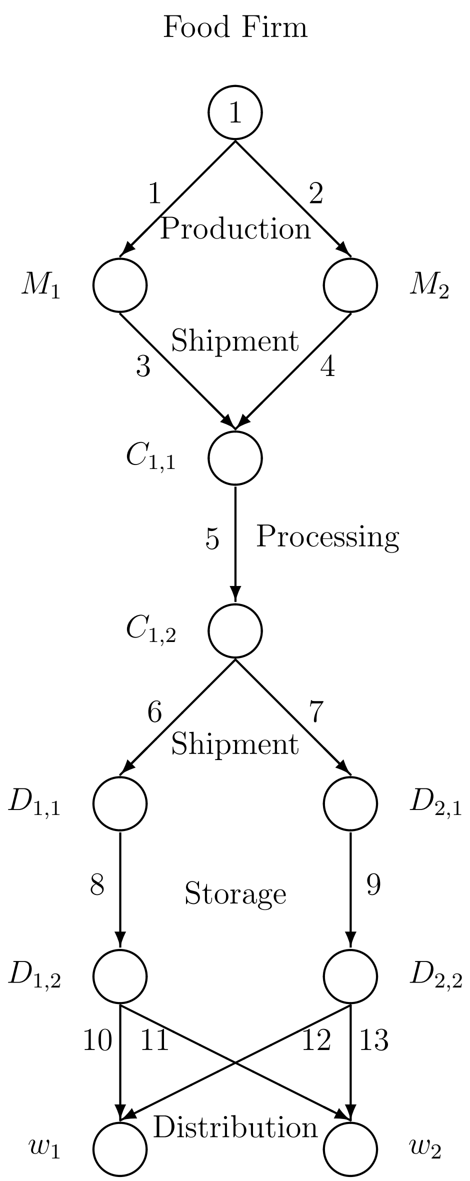


Figure 2: The Supply Chain Network Topology for the Numerical Example 1

link $a$ becomes:

$$\alpha_a = e^{-\gamma_a t_a}, \quad \forall a \in L, \tag{20}$$

where $\gamma_a$ and $t_a$ are the decay rate and the time duration associated with the link $a$, respectively; and these are given and fixed, but with the latter also adapted to factor in labor. In some cases cases, food deterioration follows the zero order reactions with linear decay (see Tijskens and Polderdijk (1996), Rong, Akkerman, and Grunow (2011), and Besik and Nagurney (2017)). In that case, $\alpha_a = 1 - \gamma_a t_a$ for a post-production link.

According to Suslow, Cantwell, and Mitchell (1997), usually, cantaloupes can be stored for 12 through 15 days at 36 to 41 degrees Fahrenheit.

The algorithm was deemed to converge if the absolute value of the difference between each computed successive iterates was less than or equal to $10^{-7}$.

**Example 1 - Baseline Example**

The input data for Example 1 are reported in Table 2. The decay rates reported in Table 2 are per day and the time duration is in days. As noted in Yu and Nagurney (2013), the cost functions are constructed utilizing the data on the average costs available on the web (see, e.g., Meister (2004a, b) and LeBoeuf (2002)) but here we handle labor costs separately.

The demand price functions are:

$$\rho_{w_1}(d) = -.001 d_{w_1} + 4, \quad \rho_{w_2}(d) = -.0001 d_{w_2} + 6.$$

There are four paths for demand market $w_1$: $p_1 = (1,3,5,6,8,10)$, $p_2 = (1,3,5,7,9,12)$, $p_3 = (2,4,5,6,8,10)$, and $p_4 = (2,4,5,7,9,12)$. There are also four paths for demand market $w_2$: $p_5 = (1,3,5,6,8,11)$, $p_6 = (1,3,5,7,9,13)$, $p_7 = (2,4,5,6,8,11)$, and $p_8 = (2,4,5,7,9,13)$.

Since Example 1 serves as the baseline example, we set the labor bounds on the links very high for all links $a \in L$ in order to see what the food product flows, demands, prices, and profit of the food firm would be in the nonpandemic situation with many available workers for all the supply chain network economic activities.

The algorithm converges to the following optimal path flow pattern:

$$x^*_{p_1} = 4.52, \quad x^*_{p_2} = 0.00, \quad x^*_{p_3} = 4.81, \quad x^*_{p_4} = 0.00;$$

$$x^*_{p_5} = 27.28, \quad x^*_{p_6} = 38.10, \quad x^*_{p_7} = 27.91, \quad x^*_{p_8} = 38.15.$$

Table 2: Labor Costs, Labor Factors, Labor Link Bounds, Arc Multipliers, Total Operational Cost, and Total Discarding Cost Functions for Example 1

| Link $a$ | $\gamma_a$ | $t_a$ | $\alpha_a$ | $\beta_a$ | $\pi_a$ | $\bar{l}_a$ | $\hat{c}_a(f)$ | $\hat{z}_a(f_a)$ |
|---|---|---|---|---|---|---|---|---|
| 1 | – | – | 1.00 | 2000.00 | 100.00 | 2000.00 | $.005f_1^2 + .03f_1$ | 0.00 |
| 2 | – | – | 1.00 | 3000.00 | 100.00 | 2000.00 | $.006f_2^2 + .02f_2$ | 0.00 |
| 3 | .150 | 0.20 | .970 | 3000.00 | 150.00 | 3000.00 | $.003f_3^2 + .01f_3$ | 0.00 |
| 4 | .150 | 0.25 | .963 | 3000.00 | 150.00 | 3000.00 | $.002f_4^2 + .02f_4$ | 0.00 |
| 5 | .040 | 0.50 | .980 | 3000.00 | 110.00 | 4000.00 | $.002f_5^2 + .05f_5$ | $.001f_5^2 + 0.02f_5$ |
| 6 | .015 | 1.50 | .978 | 4000.00 | 180.00 | 2000.00 | $.005f_6^2 + .01f_6$ | 0.00 |
| 7 | .015 | 3.00 | .956 | 4000.00 | 180.00 | 2000.00 | $.01f_7^2 + .01f_7$ | 0.00 |
| 8 | .010 | 3.00 | .970 | 10000.00 | 120.00 | 3000.00 | $.004f_8^2 + .01f_8$ | $.001f_8^2 + 0.02f_8$ |
| 9 | .010 | 3.00 | .970 | 10000.00 | 120.00 | 3000.00 | $.004f_9^2 + .01f_9$ | $.001f_9^2 + 0.02f_9$ |
| 10 | .015 | 1.00 | .985 | 8000.00 | 170.00 | 20000.00 | $.005f_{19}^2 + .01f_{10}$ | $.001f_{10}^2 + 0.02f_{10}$ |
| 11 | .015 | 3.00 | .956 | 8000.00 | 190.00 | 20000.00 | $.015f_{11}^2 + .1f_{11}$ | $.001f_{11}^2 + 0.02f_{11}$ |
| 12 | .015 | 3.00 | .956 | 9000.00 | 180.00 | 20000.00 | $.015f_{12}^2 + .1f_{12}$ | $.001f_{12}^2 + 0.02f_{12}$ |
| 13 | .015 | 1.00 | .985 | 9000.00 | 200.00 | 20000.00 | $.005f_{13}^2 + .01f_{13}$ | $.001f_{13}^2 + 0.02f_{13}$ |

The Lagrange multipliers $\lambda_a^* = 0.00$ for all links $a \in L$. The demands are: $d_{w_1}^* = 8.26$ and $d_{w_2}^* = 113.86$ with prices at the demand markets of: $\rho_{w_1} = 3.99$ and $\rho_{w_2} = 5.89$. These prices are reasonable for cantaloupes, a popular fruit in the United States. The food firm earns a profit of 329.52. Note that the data for this example is on a daily basis.

**Example 2 - Example with a Freight Service Disruption**

In Example 2 we consider the following scenario: The freight service providers associated with link 13 have taken ill so, in effect, that link for transport of the cantaloupes is no longer available and it is removed from the supply chain network topology of Figure 2. All of the other data in this example remain as in Example 1. Note that paths $p_6$ and $p_8$ for demand market $w_2$, therefore, no longer exist. We retain the path definitions as in Example 1.

The new optimal path flow pattern is:

$$x_{p_1}^* = 8.71, \quad x_{p_2}^* = 13.28, \quad x_{p_3}^* = 8.95, \quad x_{p_4}^* = 13.50;$$

$$x_{p_5}^* = 32.28, \quad x_{p_7}^* = 32.41.$$

The Lagrange multipliers for the twelve links remain all equal to 0.00. The demand price now decreases at $w_1$ but increases at $w_2$ with $\rho_{w_1} = 3.96$ and $\rho_{w_2} = 5.94$, at the respective demands: $d_{w_1}^* = 38.12$ and $d_{w_2}^* = 55.57$. The demand at demand market $w_2$ has dropped by over 50% as compared to the demand in Example 1. The food firm now earns a profit of only 219.03, a 33% drop from the profit it earns in Example 1. This example demonstrates quantitatively how the lack of labor on a single link, which is a freight one may significantly negatively impact a food firm. And, during the pandemic, it has been noted that not only labor associated with food production and processing has been impacted but freight service provision has as well.

**Example 3 - Example with a Freight Service Disruption and Loss of Productivity**

Example 3 has the same data as Example 2 except that now we consider even greater disruptions due to the pandemic. The disruptions affect the speed of processing due to the institution of social/physical distancing among the workers as well as the aftereffects of some having experienced the illness in themselves and/or their family units, so that workers are less productive than before.

Hence, in Example 3, we set the $\beta_a$ values for all $a \in L$, to one tenth of their respective value in Table 2.

The computed optimal path flow pattern for Example 3 is:

$$x^*_{p_1} = 0.00, \quad x^*_{p_2} = 1.17, \quad x^*_{p_3} = 0.00, \quad x^*_{p_4} = 6.14;$$

$$x^*_{p_5} = 21.38, \quad x^*_{p_7} = 26.18.$$

The Lagrange multipliers for the twelve links are, again, equal to 0.00.

One can see the big decrease in the cantaloupe product paths flows in Example 3, as compared to the values in Example 2. Also in contrast to Example 1, now paths $p_1$ and $p_3$ are not utilized for demand market $w_1$. The demand prices increase to $\rho_{w_1} = 3.99$ and $\rho_{w_2} = 5.96$ at the demands of: $d^*_{w_1} = 6.12$ and $d^*_{w_2} = 40.84$. The food firm only earns a profit of 72.96. This example emphasizes the importance of productivity in all supply chain network economic activities and the impact of a drastic reduction.

**Example 4 - Example with a Freight Service Disruption, Loss of Productivity, but Increase in Price Consumers Are Willing to Pay**

Example 4 has the same data as Example 3 except that the food firm is very concerned about the loss of profits and has increased marketing so that consumers are now willing to pay a higher price for the cantaloupes at both demand markets. The fixed term in each demand price function has now doubled. Hence, the demand price functions in Example 4 are:

$$\rho_{w_1}(d) = -.001 d_{w_1} + 8, \quad \rho_{w_2}(d) = -.0001 d_{w_2} + 12.$$

The remainder of the data is as in Example 3.

The computed optimal path flow pattern for this example is:

$$x^*_{p_1} = 4.46, \quad x^*_{p_2} = 18.52, \quad x^*_{p_3} = 7.72, \quad x^*_{p_4} = 21.71;$$

$$x^*_{p_5} = 59.31, \quad x^*_{p_7} = 62.22.$$

The Lagrange multipliers for the links are equal to 0.00.

The demands are now: $d^*_{w_1} = 44.54$ and $d^*_{w_2} = 104.38$ with the demand prices: 7.96 for demand market $w_1$ and 11.90 for demand market $w_2$. We are seeing during this pandemic the escalation in prices of many perishable food products. The firm now earns a profit of: 608.70, over eight times of the profit that it earns in Example 4.

**Example 5 - The Cantaloupe Supply Chain Under Further Stress Because of the Pandemic**

Example 5 represents the most stressed supply chain network example.

The data for Example 5 are as in Example 4 except for the following. The availability of labor is now severely compromised so that the $\bar{l}_a$ values are $\frac{1}{1000}$ the respective value in Example 4; that is, $\bar{l}_1 = 2.00$, $\bar{l}_2 = 2.00$, and so on. Also, the link labor factors are now $\frac{1}{10}$ their respective values in Example 4. Hence, we now have: $\beta_1 = 20.00$, $\beta_2 = 30.00$, and so on. With the demand price functions as in Example 4, the solution results in all cantaloupe product flows and Lagrange multipliers being identically equal to 0.00.

The food firm is very concerned for its viability and business sustainability in the pandemic. With extraordinary, subsequent marketing efforts, the firm has influenced consumers' willingness to pay higher prices for their nutritious product. And now the demand price functions are:

$$\rho_{w_1}(d) = -.001 d_{w_1} + 40, \quad \rho_{w_2}(d) = -.001 d_{w_2} + 60.$$

The remainder of the data remain as immediately above. Now the optimal solution is as follows. The optimal product path flows are:

$$x^*_{p_1} = 0.00, \quad x^*_{p_2} = 0.00, \quad x^*_{p_3} = 0.00, \quad x^*_{p_4} = 0.00;$$

$$x^*_{p_5} = 24.97, \quad x^*_{p_7} = 59.84.$$

The Lagrange multipliers are all equal to 0.00 except that now we have that:

$$\lambda^*_2 = 30.8309, \quad \lambda^*_5 = 65.5255.$$

Indeed, the second production site and the storage facility are utilizing the labor at their respective bound.

Observe that the food firm has no product consumed at demand market $w_1$ and only at demand market $w_2$ where $d^*_{w_2} = 72.75$. The demand price at demand market $w_2$ is 31.93. The firm, by having consumers willing to pay a higher price, now garners a profit of 407.54, even under very restricted labor and impaired productivity.

## 6. Example with Added Direct Sale Demand Markets

Given the results in Example 5, the food firm has decided to investigate the possibility of direct sales as depicted in Figure 3.

There are, hence, two added demand markets $w_3$ and $w_4$ with added links 14 and 15. Path $p_9 = (1, 14)$ and path $p_{10} = (2, 15)$. The cost data on the direct demand market links are:

$$\hat{c}_{14}(f) = .0025f_{14}^2 + .01f_{14}, \quad \hat{c}_{15}(f) = .0025f_{15}^2 + .02f_{15},$$

and the waste disposal costs are:

$$\hat{z}_{14}(f) = .0005f_{14}^2, \quad \hat{z}_{15}(f) = .0005f_{15}^2.$$

Also, the new link data parameters and labor bounds are:

$$\beta_{14} = 40.00, \quad \beta_{15} = 40.00;$$

$$\pi_{14} = 120.00, \quad \pi_{15} = 120.00;$$

$$\alpha_{14} = .99, \quad \alpha_{15} = .99;$$

$$\bar{l}_{14} = 5.00, \quad \bar{l}_{15} = 5.00.$$

The demand price functions at the new direct demand markets are:

$$\rho_{w_3}(d) = -.001d_{w_3} + 18, \quad \rho_{w_4}(d) = -.001d_{w_4} + 20.$$

The rest of the data remain as in Example 5.

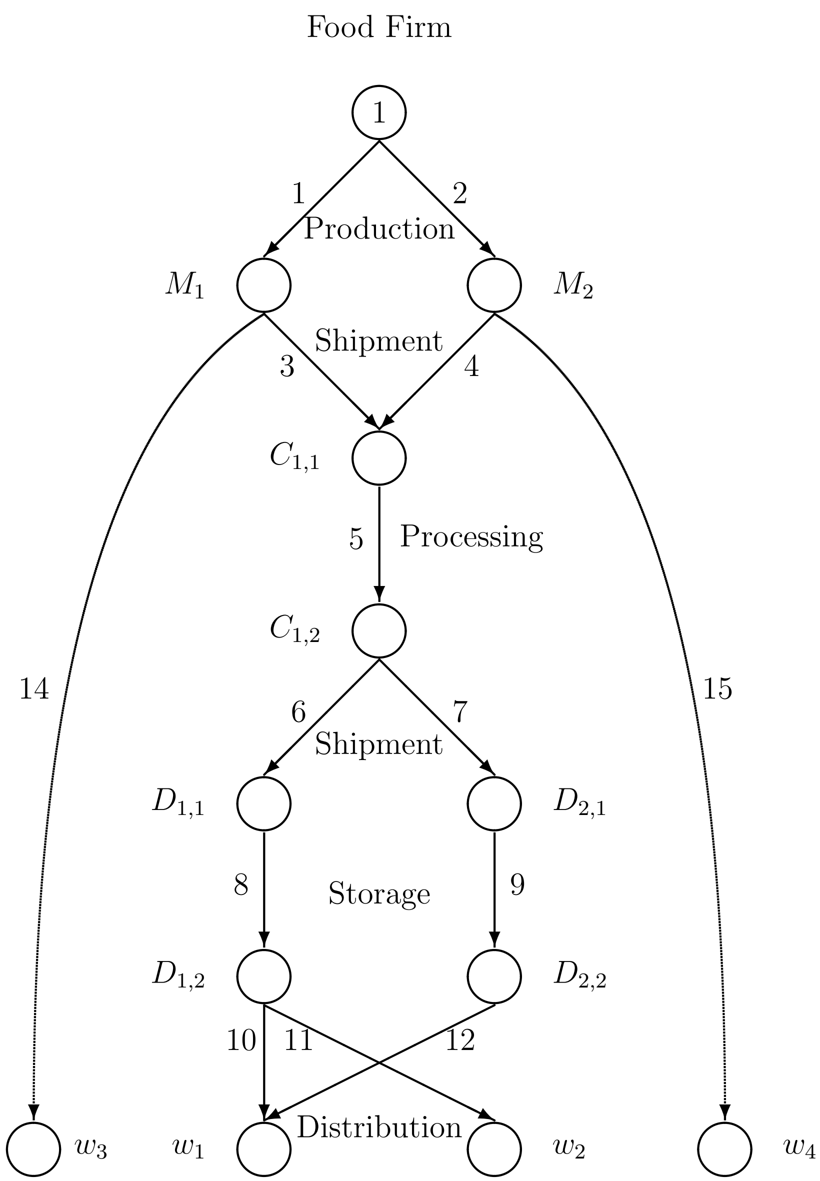


Figure 3: The Supply Chain Network Topology for Example 6

The modified projection method yielded the following optimal solution: The optimal product flows are:

$$x^*_{p_1} = 0.00, \quad x^*_{p_2} = 0.00, \quad x^*_{p_3} = 0.00, \quad x^*_{p_4} = 0.00;$$

$$x^*_{p_5} = 0.00, \quad x^*_{p_7} = 0.00,$$

$$x^*_{p_9} = 38.93, \quad x^*_{p_{10}} = 59.63.$$

and the optimal Lagrange multipliers are:

$$\lambda^*_1 = 180.76, \quad \lambda^*_2 = 368.18,$$

with all other Lagrange multipliers identically equal to 0.00.

The demand for the cantaloupes is 0.00 at demand markets $w_1$ and $w_2$. Now all sales are at the new direct demand markets with $d^*_{w_3} = 38.54$ and $d^*_{w_4} = 59.04$ at prices: $\rho_{w_3} = 17.96$ and $\rho_{w_4} = 19.94$. The profit of the food firm now rises to 1,131.31.

This example is also illustrative and shows that more direct sales, whether at farmers' markets or nearby farm stands may help a food firm in a pandemic. Many perishable product firms are now seriously considering new distribution channels with restaurants, schools, and many businesses that they would provision with food now shut down.

## 4. Summary and Conclusions and Suggestions for Future Research

The Covid-19 pandemic is a major healthcare disaster that has fundamentally transformed our daily lives and the operations of governments, businesses, healthcare, and educational institutions. It has brought to the fore the importance of essential workers, which now include farmers, food processors, and grocery workers. At a time when consumers need nutritious foods more than ever, there have been serious disruptions to food supply chains due, in part, to reduction of labor capacity. The reduction is occurring for multiple reasons, including Covid-19 illness, loss of life, fear to go to work, and the closure of food facilities due to the need for sanitization and even redesign because of the importance of social/physical distancing. Furthermore, many food items, including fresh produce, meat, fish, and dairy are perishable food products and their quality deteriorates even under the best conditions. The negative impacts of labor shortfalls and decreases in productivity are being felt in all supply chain network economic activities from production to distribution.

In this paper, we develop the first rigorous supply chain network optimization framework to explicitly include labor and bounds on labor on links for perishable food. The approach is that of a generalized network and the food firm is interested in maximizing profits (for its business sustainability) with the objective function including revenue with the demand price functions being a function of the demand and operational and discarding costs as well as costs of labor. We utilize, in effect, linear production functions that map labor on a link to product flow. A variational inequality formulation of the problem is derived, which enables the effective computation of the solution consisting of food product flows and Lagrange multipliers associated with the capacities on labor.

A series of numerical examples is presented based on a fresh produce product - that of cantaloupes, in which the quality deterioration is also captured. We consider the impacts of labor disruptions in terms of availability as well as productivity and the potential of direct demand markets on the food firm's profit, demand market prices, product flows, and demands. We emphasize that this is just the first step in modeling labor within a general supply chain network optimization framework. Future research can include adapting the model and parameterizing it for different fresh produce items, and also for meat, fish, and dairy. In addition, the possibility exists of having the arc multipliers be a function of product flow. Furthermore, since other products are perishable, such as blood, and essential in numerous medical procedures and treatments, studying the impacts of labor availability, and even donor willingness to donate during the pandemic, would merit attention.

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