$F^2\pi$: A Physical Internet Architecture for Fresh Food Distribution Networks

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Abstract: *In this paper, we introduce a Physical Internet architecture for fresh food distribution networks, with the goal of meeting the key challenges of fresh product delivery and reduce waste. In particular, we explore fuel-efficient delivery of fresh food among different stages in the logistics pipeline along with a worker-friendly delivery scheduling of the drivers. The important aspect of this proposal is the inclusion of a freshness metric and the heterogeneous, space-efficient loading/unloading of different perishable goods onto the trucks depending on their delivery requirements. The paper also discusses mechanisms for reducing empty miles of trucks and the carbon footprint of the logistics by infrastructure sharing while reducing the driver's away home time for long distance delivery. Via comprehensive simulations, the paper shows that the proposed architecture reduces the driver's away home time by ∼93% whereas improves the food delivery freshness by ∼5%.*

Keywords: *Fresh food distribution networks, physical Internet, logistics sustainability, infrastructure sharing, transportation, worker-friendly logistics.*

1 Introduction

Food is a huge business, in 2011 customers in US alone spent $1.6 trillion on food [Yu and Nagurney, 2012]. With food sourced from every part of the country and from around the world, food supply chains are extremely complex pathways from farm to the table. Health concerns have prompted a rapid rise in the demand and consumption of fresh fruits and vegetables, with consequent emphasis on cost effective supply of freshest food to the consumer. The sustainability concerns and local food movement have further emphasized the issues of freshness, quality, intelligent sourcing, and most cost effective transportation of perishable food items. The distribution process of perishable food commodities follow extremely complex pathways from their origins to the consumption points due to their constant deterioration with time, which makes the modeling and improvement of such logistics extremely difficult.

[Montreuil et al., 2010] has studied the concept of "Physical Internet" for product distribution logistics by considering similarities with and success of cyber Internet. The key issues in making the distribution logistics more efficient, flexible, cheaper, and more user friendly include (a) standardization of identification, labeling, packaging, transportation, tracking, etc, (b) sharing of physical distribution infrastructure among multiple companies, and (c) worker friendly logistics (e.g., enabling truck drivers
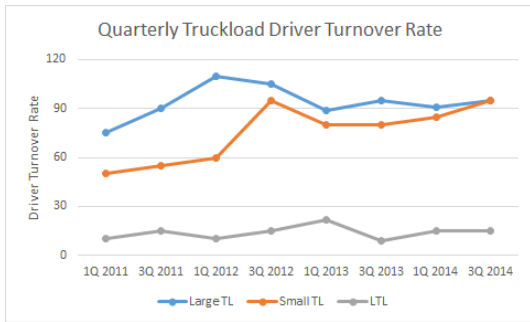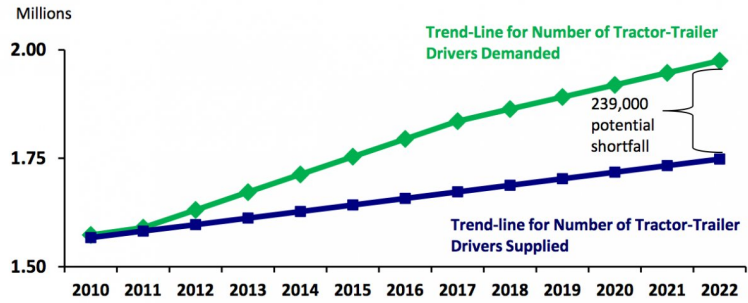
Figure 1: One key concern of todays logistics is the long driving and away-home time of truck drivers which results in (a) higher turnover rate [Jarvis, 2015] and (b) driver shortage [Badkar and Wile, 2014].

to return home for the night). While the architecture of physical Internet introduces a number of key characteristics, the requirements of food freshness remained unexplored. The key characteristic of *fresh food physical Internet (FFPI or $F^2\pi$)* is the constant deterioration in quality of a food packages based on the delay in the distribution pipeline and handling factors such as temperature, humidity, vibrations, etc. A review of the literature on food distribution networks shows that the modeling in this space remains rather simplistic. In this paper our key objective is to extend this physical Internet model to address the distribution challenges of *food logistics*.

Another key concept addressed in this paper is the notion of *infrastructure sharing* among the different agents in the food pipeline. In the traditional supply chain, the trucks often go almost half-empty in the delivery process, which increases distribution costs, transportation carbon footprint, road congestion, delivery delays, etc. Furthermore, it appears that most major companies use their own private logistics network including trucks, warehouses, etc. Although smaller companies seem to be using 3rd party logistics (3PL), it is not clear if there is really a true sharing of capacity among them – as opposed to each reserving and paying for capacity explicitly. A true pooling of resources (warehouses, trucks, drivers, loading/unloading equipment and personnel, etc) can achieve significant savings. Due to lack of sharing, the global transport efficiency is very low – in the neighborhood of 10% [Montreuil et al., 2010]. However, there are numerous issues that come up in cooperative logistics, due to the additional complexity of sharing of equipments (trucks, forklifts, RFID infrastructure, etc), facilities (distribution centers, chillers), and personnel (truck drivers, loading/unloading personnel, RFID trackers, etc). These, in turn result in complex problems of assignment, scheduling, personnel welfare, disposal of spoiled food, equipment/facility maintenance, etc.

Other than transportation capacity sharing, another key concern of current logistics is the long away-home time of the truck drivers. In fact, a significant away-from-home time (from few days to several weeks) for drivers has traditionally caused very high turn-over rate in this business and consequent impact on service quality [Montreuil et al., 2010] which in tern results in driver shortage [Badkar and Wile, 2014] as depicted in Fig. 1(a)-(b). Fig. 1(a) shows that the truckload industry as a whole replaced the equivalent of 95% of their entire workforce of drivers by the end of 2014. In this paper we explore the idea of *shared logistics to reduce trucker's time away from home*, by dividing the long journey of a truck driver among multiple drivers. This requires rather close cooperation and interactions among the agents in the food pipeline, that are used to work in isolation. The continuous perishability of the food products further complicates the matter.

The paper shows through extensive simulations that the proposed $F^2\pi$ framework reduces the driver's away home time by ∼93% whereas improves the delivery freshness quality of the food packages by

∼5%. To the best of our knowledge, this is the first work to develop the truck scheduling, considering the *environmental*, *economic* as well as *social* aspects. Even if we address this in the context of fresh food logistics, our methodology is generic enough to be adapted to other logistics systems as well.
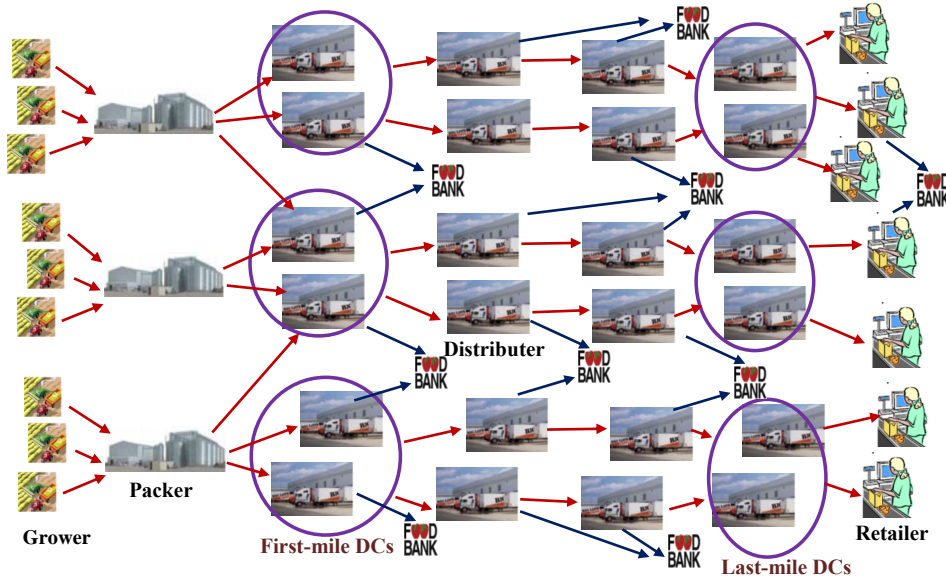

Figure 2: A schematic of our assumed food network model.

The outline of the paper is as follows. We first provide an overview of the $F^2\pi$ architecture in Section 2.1. In section 2.2 we discuss the freshness quality metric using a time-temperature indicator, that is used for the packing, mixing and distribution of the the perishable products in the later sections. In section 3 we address the distribution and forwarding of the food packages among different distribution centers, along with a worker-friendly, fuel-efficient truck scheduling mechanism. Performance evaluations are reported in Section 4. The related works are summarized in section 5. Section 6 concludes the paper.

2 Overview of a Shared $F^2\pi$ Architecture

The basic diagram of a food logistic is shown in Fig. 2. Foods from farmlands are taken to the packing centers where they are sorted and packed for delivery to any of the nearest distribution centers (DCs) and retailers. If the quality of some products deteriorate significantly at any stage of the food pipeline, they are sent to the *food banks* [Lipinski et al., 2013] where they are consumed at lower cost or at free to the people who need them. By distributing the food products that otherwise would be wasted to the food banks, the food loss in the chain can be drastically reduced. The entire process is fairly complicated, due to the inter-dependencies of several issues, ranging from environmental to social, or from economical to food freshness.

2.1 From Private Logistics to Shared Logistics

In the traditional supply chain, the trucks often go empty for a variety of reasons besides lack of sharing. It is reported that in USA the trailers are approximately 60% full in the distribution process. The global transport efficiency is recently estimated to be lower than 10% [Montreuil et al., 2010]. The effect is not

just merely efficiency related. This results in more number of truck runs, which increases its environmental impact as well as the transportation costs. Also higher truck runs turn the drivers to become modern cowboys [Montreuil et al., 2010], which results in driver shortage and higher turnover rate. The biggest reason for this inefficiency is that in traditional supply chain different vendors use their own private network/trucks for product delivery and do not frequently coordinate with each other. For an example Walmart and Target use their own food network as well as their trucks in the delivery process which reduces the transportation efficiency. Other reasons include: (a) the need to return the truck and product containers back to the source so that they will be available quickly to handle the next shipment, and (b) lack of demand or unavailability of suitable product or its containers to fill the truck on is backwards journey.

To overcome this, in a shared $F^2\pi$, the responsibilities of the *distribution companies* and the *shipping companies* are first separated. In $F^2\pi$ the trucks are not owned by the distribution companies. Rather the trucks are owned by some shipping companies (similar to UPS, FedEX etc) that take delivery orders from different DCs and deliver them to the corresponding destination DCs. This separation serves two key purposes. First, if the truck journeys are scheduled properly, their space can be shared to deliver the demands of different distribution companies. This reduces the empty miles, improves transportation efficiency as well as reduces carbon footprint and transportation costs. On the other hand reducing empty miles reduces the driving burden of the drivers too. Second, in such a model, the containers can be provided by the shipping companies. Thus in a truck's journey, the containers move with the truck, loaded-unloaded with the packages that are to be delivered in between the DCs. In this model returning the empty containers back to the source is not needed. Such a shared model is promising for improving the overall efficiency of the logistics system, however brings some new challenges. Scheduling the truck in this shared model needs to account for several factors such as: (a) transportation efficiency, (b) driver's away home time, (c) delivery freshness of the food packages, and (d) road congestion especially in city areas at peak hours. Some of these objectives are contradictory; for example, as the trucks are shared among the DCs, there is always a tradeoff between capacity utilization and loss of quality of perishable products due to additional delays in waiting for product to carry and loading/unloading. These distribution decisions are taken by consulting with the 3PL operators to ensure collaborative logistics, instead of private logistics decisions taken by the individual companies.
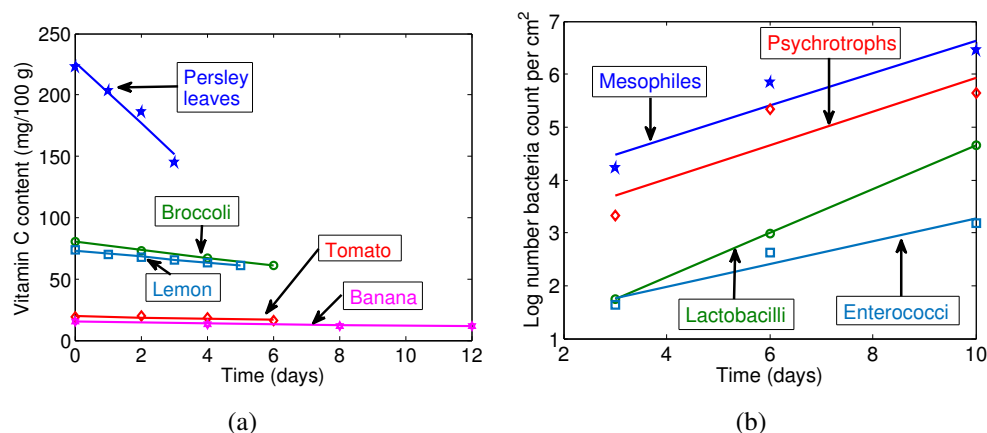

Figure 3: (a) Vitamin C degradation in different vegetables at $20°$ C (data obtained from [Mazurek and Pankiewicz, 2012]). (b) Bacterial content in chicken meat at $2°$ C (data obtained from [Reddy, 1981]).

2.2 Modeling the Perishability Metric

Traditional supply chain logistics are researched more towards reducing the transportation cost in the delivery process. In $F^2\pi$, one of the important factors is the food freshness, that needs to be integrated with the tradition logistics. Fresh food packages deteriorate in quality over time according to complex biochemical processes that depend on the food type, initial quality, temperature, humidity, vibrations, bacterial level, and bruises during storage/transportation. The deterioration as a function of time t can be described by a non-decreasing function that is henceforth denoted as $\zeta(t)$. The deterioration of food products are nothing but biochemical reactions, thus $\zeta(t)$ can be modeled as a function of some measurable parameters related to the reaction that determines the quality loss.

We describe a metric for estimating the degradation of a measurable parameter of a food product using its *time-temperature indicator*. Like any other biochemical reactions, in food products as well, certain parameter **A** gets converted to another, say **B** over time. As the reaction proceeds, the concentration of **A** decreases, whereas that of **B** increases. The concentration loss (of **A**) or gain (of **B**) of a particular ingredient at any instance can be described by the following equation:

$$\frac{dC}{dt} = k.C^n \tag{1}$$

where C is the concentration of the ingredient, k is the rate of degradation that depends on temperature and other factors, and n is the order of reaction that is either 0 (zero order) or 1 (first order) for most of the food products. Food products like fruits or vegetables generally follow zero-order degradation or linear decay, whereas products like meat or fish follow first-order degradation of exponential decay. Thus the quality can be measured by checking the concentration of certain ingredients in the food products. For example concentration of Vitamin C or sulfur can be the quality indicators for different fruits or vegetables, whereas the concentration of bacterias like Mesophiles, Psychrotrophs, Lactobacilli, Enterococci, Coliforms etc can be the quality indicators for meat products.

The rate of concentration loss or gain k at different temperatures can be modeled using Arrhenious equation as follows

$$k = k_0.e^{-\frac{E_a}{\mathfrak{R}\Gamma}} \tag{2}$$

where k_0 is a constant, E_a is the activation energy, $\mathfrak{R}$ and Γ are gas constant and absolute temperature respectively. Thus if a food product goes through multiple phases $i = 1, 2, ..., m$ with time t_i at i-th stage and rate k_i (based on temperature Γ_i), then the end concentration of an ingradient

$$
\begin{aligned}
C &= C_0 \pm \sum_{i=1}^{m} k_i t_i = C_0 \pm \sum_{i=1}^{m} k_0.t_i.e^{-\frac{E_a}{\mathfrak{R}\Gamma}} \quad \text{for zero-order} \\
C &= C_0.e^{\pm \sum_{i=1}^{m} k_0.t_i.e^{-\frac{E_a}{\mathfrak{R}\Gamma}}} \quad\quad\quad\quad \text{for first-order}
\end{aligned}
\tag{3}
$$

where C_0 is the initial concentration of the ingredient. The parameter k can also be obtained from experimental results at different temperatures. In equation(3) the $\pm$ sign represents the loss or gain of concentration depending on the type of the measurable parameter. For example, the Vitamin concentrations of fruits or vegetables decay over time, whereas the bacterial growths on meat products adds up with time. Fig. 3(a) shows the Vitamin C degradation of different vegetables over time at $20°$ C which shows the linear decay, thus k's are the slopes of the graphs. Also the exponential growth of certain bacterias on meat substances are shown in Fig. 3(b) where $\ln(k)$'s are the slopes.

With these, we can scale a perishability function of a food product $\zeta(t)$ from the level of concentration of some measurable parameters. It suffices to assume that ζ belongs to the real range [0, 1] where 1 means

that the product so far has not suffered any quality loss and 0 means that product has no value. Thus if we know the storage time and temperature of the chain in different stages, we can estimate the delivery quality of a product using the above approach. In reality because of different disturbance in the food chain (vibrations, change in temperature or humidity etc) the quality deteriorates faster or slower than the theoretical expected rate.

3   Product Distribution and Truck Scheduling

With these we next formulate our truck scheduling problem with the vision of sharing the truck space to deliver food packages among multiple distribution companies. As mentioned earlier, one of the concerns of traditional logistics is the long driving time of the truck drivers, that makes them stay away from home for days and sometimes for weeks. To cope with this, in $F^2\pi$ the delivery of food packages are made using shorter hops among the distribution facilities. Making shorter trips reduces the driver's away home time, which improves the quality of their personal, social and family life and at the same time reduces their turnover rates [Meller and Ellis, 2012]. An ideal case of this is shown in Fig. 4 where the trucks have their certain coverage areas/domains within which they distribute food products among different DCs. The long driving distance in between DC_s and DC_d is divided into shorter hops, that are

Figure 4: Inter and intra-domain schemes between the DCs.

determined by *inter-domain delivery strategies*. When a truck gets order to deliver something from one DC to multiple other DCs, it checks whether the nearby DCs have to deliver food packages among each other. It then makes its schedule accordingly so that its fuel efficiency or delivery freshness is maximized and at the same time the driver can return to the starting point (DC_s) within his scheduled hours. The appropriate scheduling of the trucks within their coverage domains brings the need for developing smart *intra-domain distribution strategy (IntraDS)*. Proper integration of inter and intra-domain strategies need considerations of storage/traveling time of the individual food packages as well as their delivery requirements, while improving the transportation efficiency of the trucks and their driver-friendly schedules. We discuss the routing and scheduling strategies in these two domains in the following subsections.
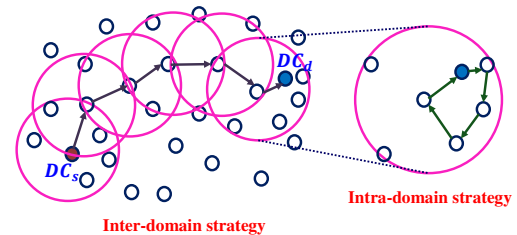
3.1   Inter-domain strategy

The inter-domain strategy depends on the coverage areas of the trucks. By using the coverage areas of the trucks, as well as the availability of the other transportation modes (rail, river etc.), the DC_s generates the connectivity graph among the DCs and then implement a routing scheme on this connectivity graph. The routing scheme is similar to the *shortest-path routing* [Tanenbaum, 2002] in computer networks, where the cost function may be a function of a number of factors, like (a) expected delay (waiting time in the DC + travel time), (b) end-to-end delivery quality, (c) the business policies among the DCs etc. The business relationships among the DCs can be of two types: *customer-provider*, where a DC rents out some storage space to others at some cost, or it can be *peer-peer*, where the DCs belong to the same company. The business policies among the DC_s and the other intermediate DCs determine the cost of renting out the storage space. Also in $F^2\pi$, the DCs need to pay extra *carbon taxes* [Benjaafar and Chen, 2014] for using road transportation, and so prefers river/rail transportation wherever available. Imposing carbon taxes will encourage the DCs to use transportation modes that are more environment friendly. After considering the above factors, the DC_s determines the route to deliver its products to DC_d and place
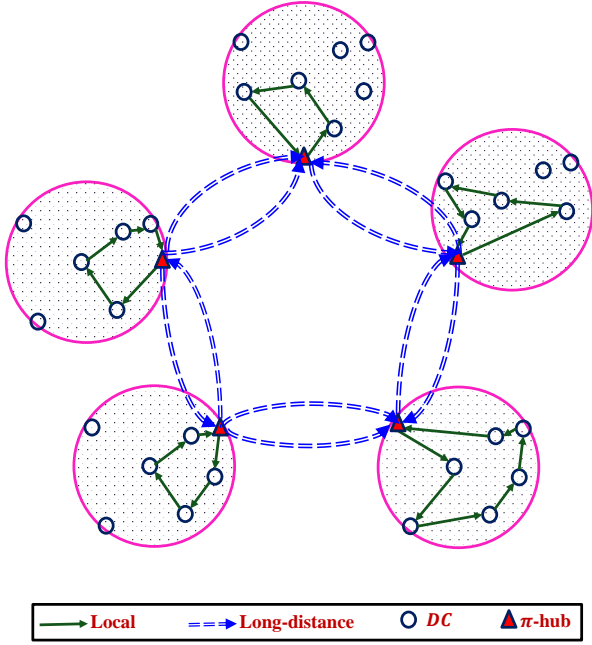
Figure 5: Integration of local and long-distance food logistics.

		Indices
i, j	$\triangleq$	Index for distribution centers $(1, ..., \mathfrak{N})$ that are within the coverage areas of the trucks
ℓ	$\triangleq$	Index for transit-segments of the trucks $(1, ..., \mathfrak{T})$
t	$\triangleq$	Index for types of products $(1, ..., \mathcal{T})$
		Transportation variables
$p_{ij}^{t\ell}$	$\triangleq$	Amount of type t loaded at DC_i for delivery at DC_j at the ℓ-th transit-segment
$d_{ij}^{t\ell}$	$\triangleq$	Amount of type t unloaded at DC_i from DC_j at the ℓ-th transit-segment
$R_{ij}^{t\ell}$	$\triangleq$	Amount of type t that are on the truck for delivery at DC_i from DC_j at the ℓ-th transit-segment
$L^{t\ell}$	$\triangleq$	Truck load of type t at transit-segment ℓ
S_{ij}^{t}	$\triangleq$	Delivery request from DC_i to DC_j of type t
T_{ij}	$\triangleq$	Time of travel from DC_i to DC_j
B_{j}^{ℓ}	$\triangleq$	Time when the truck delivers at DC_j in the ℓ-th transit-segment
		Decision Variables
$x_{ij}^{\ell} \in 0, 1$	$\triangleq$	Whether or not the truck goes from DC_i to DC_j at the ℓ-th transit-segment

Figure 6: Table of Notations

the delivery order to the truck dealers.

Notice that some of these DCs can be considered as π-transit, π-switch, π-bridge, π-gateway, π-hub [Montreuil et al., 2010] etc depending on their role in the distribution logistics. For example Fig. 5 shows a scenario that integrates the *local* and *long-distance* logistics. In this figure the local and regional packages are brought at the π-hubs for long-distance delivery which is the distribution of packages in between different regions. The local distribution can be done by small trucks or trailers, whereas the large trucks (18 wheelers) are used for the delivery in between the hubs.

3.2 Intra-domain strategy

After getting the delivery orders from the DCs, the shipping companies schedule their trucks for fulfilling the delivery orders, after consulting with the 3PL operators. Each truck driver maintains his maximum continuous driving time and within that time he tries to serve as many orders as he can to maximize the design objectives. The Intra-domain routing strategy of the trucks is similar to the *travelling salesman problem (TSP)* [Applegate et al., 2007], *pickup and delivery problem* [Berbeglia et al., 2010] and *ride-sharing problem* [Ma et al., 2013], but have a number of differences. First most of the schemes proposed for the above-mentioned problems try to minimize the overall travel time of the vehicles, whereas our objective is to maximize the fuel-efficiency, reduce the empty-miles and at the same time fresh delivery of the food products to their destinations. Second the above-mentioned problems do not have any maximum delay bound, whereas our scheme have to consider the maximum driver's away home time, which puts an upper limit of the travel time of the trucks. Third in the above related problems, a vehicle needs to go at every location at least once and serves their requirements, whereas in our scheme a truck driver may skip fulfilling the demands of some DCs within its coverage area, if the maximum time-limit cannot be

maintained or if visiting few DCs effectively reduce the performance objectives. Those skipped packages will be delivered by other trucks. Also contrary to the previous works, in our scheme the truck driver may visit the DCs more than once, which makes the problem more complicated. Also notice that there may be multiple roads (channels) corresponding to one hop. It may happen that some roads are busy in day time, but not in evening hours, so taking those roads at evening time is better, whereas in daytime other roads are preferred. While scheduling the trucks, the scheduler considers only the road that takes minimum transit time. Notice that the proposed truck scheduling can be applied for distributing packages in both local and long-distance logistics. We next model the optimization problem and then discuss the complexity of IntraDS in the following subsections.

3.2.1 Problem formulation of IntraDS

The objective of IntraDS is mainly twofold. First is to maximize the efficiency of the transportation, which we define as the amount of product delivery per miles/time. Second is to maximize the cumulative delivery quality of all the packages, which we define as the product of the delivery quality and the delivery amount. Thus our objective function is to

$$\text{Maximize} \quad \mathbb{A} \frac{\sum_i \sum_j \sum_t \sum_\ell d_{ij}^{t\ell}}{\sum_i \sum_j \sum_\ell x_{ij}^\ell . T_{ij}} + \mathbb{B} \sum_j \sum_t \sum_\ell \sum_i \left(\mathbb{Q}_{ij}^t - k^t B_j^\ell \right) d_{ji}^{t\ell} \tag{4}$$

Here $\mathbb{Q}_{ij}^t$ is the initial average Vitamin C content (or other indicators) of the t-th type packages from DC_i to DC_j and k is the quality decay rate at the truck temperature. The term $\frac{\sum_i \sum_j \sum_t \sum_\ell d_{ij}^{t\ell}}{\sum_i \sum_j \sum_\ell x_{ij}^\ell . T_{ij}}$ is defined as the *efficiency-factor*, whereas $\sum_j \sum_\ell \sum_i \sum_t \left(\mathbb{Q}_{ij}^t - kB_j^\ell \right) d_{ji}^{t\ell}$ is defined as the *quality-factor*. $\mathbb{A}$ and $\mathbb{B}$ are the weights of the efficiency-factor and the quality-factor respectively. Equation(4) assumed linear decay, however exponential decay can be modeled similar to equation(3). The necessary variables are listed in Fig. 6, where the term *transit-segment* is defined as follows. If a truck goes from $DC_1 \to DC_2 \to DC_3 \to DC_1$, then the first transit-segment starts at DC_1 and ends at DC_2, the second segment starts at DC_2 and ends at DC_3 and so on. The maximum number of transit-segments allowed for a truck is assumed to be $\mathfrak{T}$. The source of a truck is denoted as $\circledS$. The constraints are defined as follows.

Continuity constraint: If the truck comes at point j at transit-segment ℓ, then it needs to leave from j at transit-segment $\ell+1$, i.e.

$$\sum_i x_{ij}^\ell = \sum_k x_{jk}^{\ell+1} \quad \forall j, \forall \ell \in \{1, 2, ..., \mathfrak{T}-1\} \tag{5}$$

Also a truck loads and unloads goods at DC_i only when it is at the DC_i, i.e.

$$\sum_j \sum_t d_{ij}^{t(\ell+1)} \leq \mathbb{M} \sum_k x_{ki}^\ell$$

$$\sum_j \sum_t p_{ij}^{t(\ell+1)} \leq \mathbb{M} \sum_k x_{ki}^\ell \quad \forall i, \forall \ell \in \{1, 2, ..., \mathfrak{T}-1\} \tag{6}$$

where $\mathbb{M}$ is at least as high as the maximum amount of objects that can be picked-up/delivered at any particular DC. The amount of goods that is loaded is less than the corresponding delivery requests. Also the cumulative amount of loading and unloading is equal. The trucks need to deliver all the packages that

they have loaded before ending their journey. These give rise to the following set of constraints

$$\sum_\ell p_{ij}^{t\ell} \le S_{ij}^t \qquad \forall i, \forall j, \forall t$$

$$\sum_\ell d_{ij}^{t\ell} = \sum_\ell p_{ji}^{t\ell} \qquad \forall i, \forall j, \forall t$$

$$R_{ji}^{t\ell} = R_{ji}^{t(\ell-1)} + p_{ji}^{t\ell} - d_{ij}^{t\ell} \qquad \forall i, \forall j, \forall \ell, \forall t \qquad (7)$$

$$d_{ij}^{t\ell} = R_{ji}^{t(\ell-1)} \times \sum_k x_{ki}^{\ell-1} \qquad \forall i, \forall j, \forall \ell \in \{1, 2, ..., \mathfrak{T}-1\}, \forall t$$

$$R_{ji}^{t\mathfrak{T}} = 0 \qquad \forall i, \forall j, \forall \ell, \forall t$$

Truck-load constraint: The truck-load at any transit-segment ℓ is equal to the truck-load at its previous transit-segment and the difference of the amount that is loaded and unloaded at ℓ. Also the truck-load at any ℓ is less than the truck capacity C.

$$L^{t1} = \sum_i p_{\circledS i}^{t1}$$

$$L^{t\ell} = L^{t(\ell-1)} + \sum_i \sum_j \left(p_{ij}^{t\ell} - d_{ij}^{t\ell} \right) \quad \forall \ell \in \{2, ..., \mathfrak{T}\}, \forall t \qquad (8)$$

$$\sum_t L^{t\ell}.\mathcal{V}^t \le C \ \ \forall \ell \in \{2, ..., \mathfrak{T}\}$$

where $\mathcal{V}^t$ is the volume of the container type t. Constraint(8) simply assumes that multiple containers of different sizes always fit within a truck as far as their cumulative volume is less than the truck's capacity. This is an over-estimation of the packing ability of the containers. However in reality this over-estimated amount of packages can be passed to a *loading module* that loads a fraction of the assigned packages by solving typical 3D-bin packing [Hifi et al., 2010]. The remaining packages can be carried by other trucks while they are scheduled. Notice that due to the use of modular containers or π-containers [Montreuil et al., 2010], the error due to this over-estimation is limited.

Travel time constraint: The total travel time is bounded by the minimum and maximum driving time allowed, i.e.

$$T^{\min} \le \sum_i \sum_j \sum_t x_{ij}^\ell.T_{ij} \le T^{\max} \qquad (9)$$

Also the delivery time at the DCs are recorded as follows:

$$B_\circledS^1 = 0$$

$$B_j^\ell = \sum_i x_{ij}^{\ell-1} \times \left(B_i^{\ell-1} + T_{ij} + w_j \right) \quad \forall j, \forall \ell \in \{2, ..., \mathfrak{T}-1\} \qquad (10)$$

where w_j is assumed be the time for pickup/delivery at the delivery point j.

Delivery constraint: The delivered packages should ensure its required freshness limit $\mathfrak{F}$, i.e.

$$\left(\mathbb{Q}_{ij}^t - k^t.B_j^\ell \right) d_{ji}^{t\ell} \ge \mathfrak{F}.d_{ji}^{t\ell} \qquad \forall i, \forall j, \forall \ell, \forall t \qquad (11)$$

This constraint assume linear decay, whereas exponential decay can be modeled in a similar fashion.

Other constraints: Also the truck should start and end at the starting point. To keep the problem simple, we assume that the truck does not visit a point more than η. For our simulations, we keep η to be

2 for simplicity. These give rise to the following constraints

$$\sum_i \sum_\ell x^\ell_{\circledS i} + \sum_j \sum_\ell x^\ell_{j\circledS} = 2$$

$$\sum_i \sum_\ell x^\ell_{ij} \leq \eta \;\; \forall j \text{ other than the source}$$

$$\sum_i \sum_j x^\ell_{ij} \leq 1 \;\; \forall t \qquad \sum_i x^1_{\circledS i} = 1 \tag{12}$$

$$\sum_j \sum_\ell x^\ell_{j\circledS} = 1 \qquad \sum_j \sum_{\ell=2}^{\mathfrak{T}} x^\ell_{\circledS j} = 0$$

We next define two instances of IntraDS, based on the values of $\mathbb{A}$ and $\mathbb{B}$ in equation (4). When $(\mathbb{A}, \mathbb{B}) = (1, 0)$, the problem becomes efficiency-factor maximization problem, named E-IntraDS, whereas $(\mathbb{A}, \mathbb{B}) = (0, 1)$ makes it quality-factor maximization problem which we call Q-IntraDS.

3.2.2 Complexity of IntraDS

The IntraDS can be proven to be NP-complete as shown in the following theorem.

Theorem 1. *The problem IntraDS is NP-complete.*

Proof. We first introduce a decision version of IntraDS as follows: determine whether there exists a feasible route and loading-unloading schedule such that the objective function of equation(4) is more then a constant $\mathbb{U}$. Clearly, given a route and loading-unloading schedule, the problem is verifiable in polynomial time, i.e. IntraDS $\in$ NP.

Now we reduce the TSP to the IntraDS problem. We define an instance of the IntraDS problem as follows: we assume that there is no intermediate pickup. Thus the truck loads all the products at the origin and after delivery, it returns to the origin. We also assume that $\mathbb{A} = 1$ and $\mathbb{B} = 0$ in equation(4). The total amount of packages loaded at the origin is one unit. This reduction transforms a TSP instance into a IntraDS instance. Thus there exists a feasible solution of IntraDS such that the objective function is more than $\mathbb{U}$ if and only if TSP has a route at cost less than $\frac{1}{\mathbb{U}}$. Thus IntraDS is verifiable in polynomial time and there exists a polynomial time reduction of TSP to IntraDS. This completes the proof. $\square$

As the problem is NP-complete, we have proposed a genetic algorithm based meta-heuristics in [Pal and Kant, 2016b] to solve this problem. In this paper we have omitted the detailed discussion of genetic algorithm due to space constraint.

4 Performance Evaluation:

4.1 Performance of Inter-domain forwarding

We consider a truck that carries broccolis that have the Vitamin C content of 99.9 mg/100 g initially. We assume that the broccolis are maintained at two types of environment, one is a chilled environment of $2°$ C. In another case they are carried at $20°$ C. Also at $2°$ C, $k = 0.0408$ mg/100 g in an hour, where at $20°$ C, $k = 0.1375$ mg/100 g in an hour [Mazurek and Pankiewicz, 2012], [Albrecht et al., 1990], [Lee and Kader, 2000].

Effect on driver's driving time: We first demonstrate the advantage of using short hops for delivery among the DCs. We consider a scenario where a truck needs to deliver certain amount of packages to a
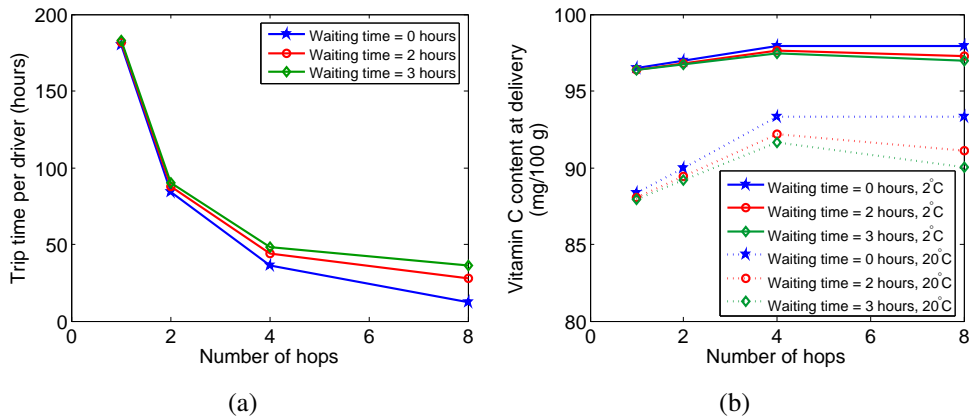
Figure 7: Variation of (a) the trip time of the drivers, and (b) Vitamin C content at delivery with the number of hops.

DC that requires 48 hours of driving time. A driver drives 12 hours continuously, takes rest for 12 hours and then starts driving again. If this job needs to be done by a single driver (one hop scenario), then it takes almost 84 hours for the driver to reach at the destination, deliver the packages and then returning back at the starting point takes another 96 hours. This long trip time deteriorates the overall quality of the products as well as increase the driver's time away from home. In case of two hops, the driver needs to unload the packages at the halfway point (a DC that is 24 hours apart), from where another driver loads the packages and delivers them to the ultimate destination DC. This reduces the trip time of each driver as seen from Fig. 7. As seen from Fig. 7(a), by introducing 8 hops in between the DCs, the trip time is reduced by ∼93%. Also whenever a driver reaches in a delivery point, it needs to wait for the workers to load/unload the packages to/from the truck, which we vary from 0-3 hours in Fig. 7. Obviously the trip time increases due to additional waiting time due to additional loading-unloading.

Effect on delivery freshness: Also notice that increasing the number of intermediate hops improves the delivery freshness. From Fig. 7(b) we can observe that at 20° C, by introducing 8 hops, the Vitamin C content in the delivered broccolis are improved by ∼5%, when the waiting time for loading/unloading is assumed to be zero. With the increase in intermediate loading-unloading, the Vitamin C content starts decreasing. With 8 intermediate hops, the Vitamin C content decreases by ∼3% when the loading-unloading time increasing from 0 to 3 hours. Fig. 7 clearly shows the benefits of using multiple hops for building a worker-friendly fresh food delivery chain. From Fig. 7(b) we can also observe that the broccolis retain their Vitamin contents higher in a chilled atmosphere; the Vitamin contents drops by ∼5% if the temperature increases from 2° C to 20° C. Because of additional loading/unloading time in the intermediate points, deciding the number of intermediate delivery hops is an important choice for determining the delivery of fresh quality food, as well as forming a worker-friendly food logistics.

4.2 Performance of Intra-domain forwarding

We next compare our proposed Intra-domain delivery schemes E-IntraDS and Q-IntraDS using a small network consists of five DCs. The travel time in between the DCs are shown in Table 2 where the DCs are denoted as **A** to **E**. We ignore the pickup/delivery time for simplicity. We use AMPL solver [Fourer et al., 1989] for solving the optimization problem. We consider two types of vegetables: raspberries and broccolis. We assume that the containers ensure that the vegetables are kept at 2° C, which corresponds to the deterioration rates of 0.0229 mg/100 g and 0.0408 mg/100 g per hour respectively. Their
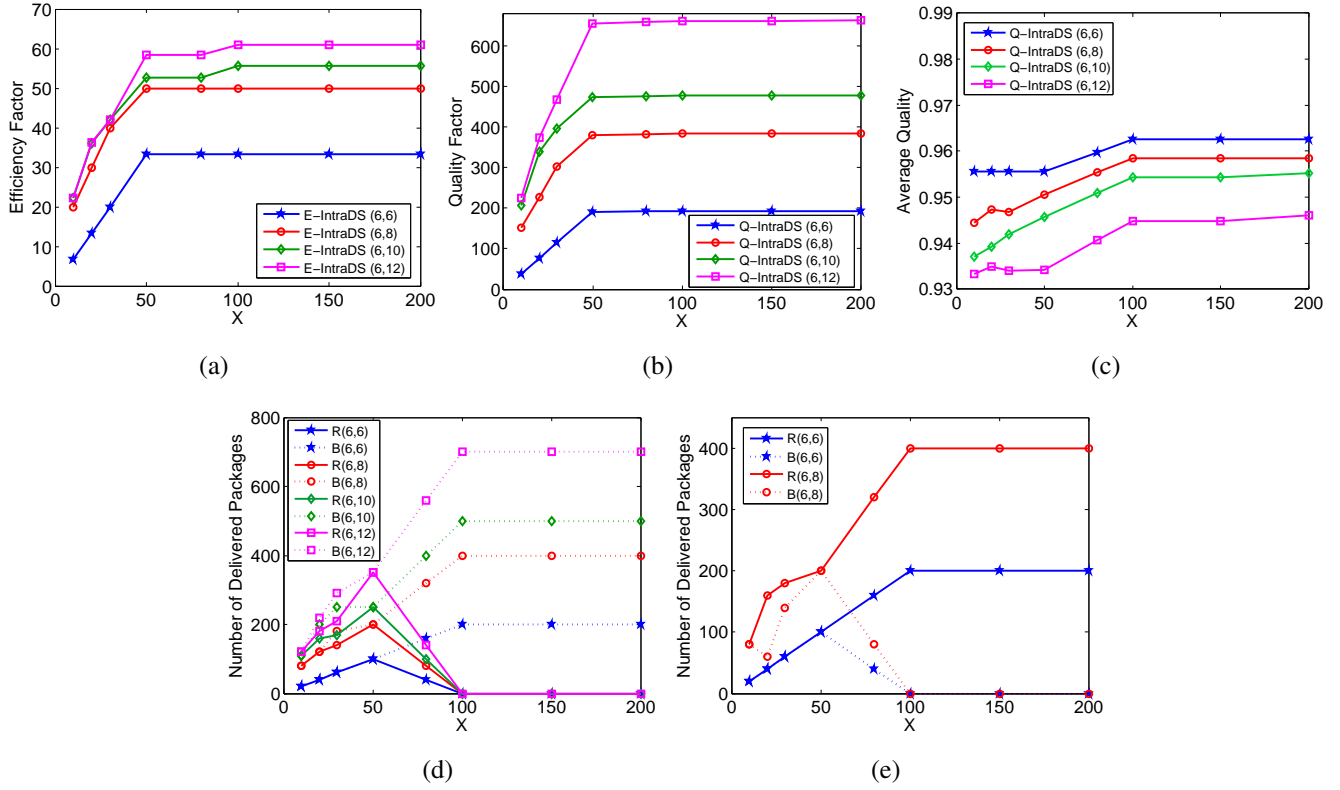
Figure 8: Variation of (a) efficiency-factor, (b) quality-factor, (c) average delivered quality, and (d), (e) number of delivered packages, with different X. In the legends $R(a,b)$ and $B(a,b)$ denote raspberries and broccolis, and a and b are $T_{\min}$ and $T_{\max}$ respectively.

initial Vitamin C content is assumed to be 27 and 99.9 mg/100 g. We have normalized these decay rates by assuming the delivery thresholds of strawberries and broccolis to be 25 and 95 mg/100 g respectively, thus their percent deteriorations are 1.15% and 0.83% per hour respectively. $\Im$ is assumed to be 0.85. The demand matrix of each one of these two types of vegetables among the DCs as shown in Table 1. In Table 1 X is a variable, which is varied from 10 to 200 for our simulations. We assume all the packages are of same size of unit volume. The truck has a vol-

Table 1: Order matrix

	A	B	C	D	E
A	-	X	X	X	X
B	-	-	X	-	-
C	X	-	-	-	X
D	X	-	-	-	X
E	X	-	X	X	-

Table 2: Time matrix (hours)

	A	B	C	D	E
A	-	2	3	3	3
B	2	-	2	3	3
C	3	2	-	1	1.5
D	3	3	1	-	1
E	3	3	1.5	1	-

ume of 100, i.e. its capacity limit is of 100 packages. Also the $T_{\min}$ is assumed to be 6 hours, whereas T_{max} is varied in between 6 to 12 hours.

Effect on transportation efficiency: Fig. 8(a) compares the efficiency-factor of E-IntraDS with increasing X. From Fig. 8(a) we can observe that the transportation efficiency starts increasing with the increase in X. This is because with higher X, the truck is loaded with more packages, which increase its efficiency. But after a certain point, the efficiency saturates. Interestingly, this point is almost similar to all $(T_{\min}, T_{\max})$ values, which is $X \sim 50$ in Fig. 8(a). Also we can observe that by increasing $T_{\max}$ from 6 hours to 12 hours increase the efficiency by $\sim 80\%$-200%. This is because with higher $T_{\max}$, the truck gets more time to schedule its route to improve its efficiency, which is limited for lower $T_{\max}$.

Effect on delivery quality: Fig. 8(b) shows the quality-factor of Q-IntraDS with varying X. The quality-factor increases by 3-5 times with the increase in X from 10 to 100, as more number of packages are transported and delivered. But after $X = 100$, this factor starts saturating. Similar to Fig. 8(a), the saturation point is similar for all $(T_{\min}, T_{\max})$ values. We can also observe that the quality-factor increases by 4 times, as $T_{\max}$ is increases from 6 hours to 12 hours. This is because with higher $T_{\max}$, the truck's travel time increases as well as the number of loading-unloading, which increase the quality-factor.

Fig. 8(c) shows the delivery quality of the packages with different $(T_{\min}, T_{\max})$ pairs. We can observe that the delivery quality decreases with the increase in $T_{\max}$. This is because the higher travel time results in more waiting time of the packages within the truck, which increases their average spoilage.

Effect on product mixing: Fig. 8(d) shows the effect of Q-IntraDS in product mixing. When the demand is low, i.e. X is less compared to the truck capacity, both strawberries and broccolis are carried and delivered. Whereas with the increase in X, more number of broccolis are transported. This is because the percent decay rate of broccolis is much less than that of strawberries, thus delivering more amount of broccolis improve the quality factor, compared to carrying strawberries. We can also observe that the amount of broccolis increase by ∼4 times, when $T_{\max}$ is increased from 6 hours to 12 hours. This is obvious because of the higher number of carried packages with increased travel time.

In Fig. 8(d) the number of broccolis delivered is always higher than raspberries, as the spoilage rate of broccolis is lesser. With such an objective function, the products that are more perishable is always given lower preference. To overcome this limitation, the objective function can be modified as $\sum_j \sum_t \sum_\ell \sum_i \left\{ \alpha \left(\mathbb{Q}_{ij}^t - k^t B_j^\ell \right) d_{ji}^{t\ell} + (1 - \alpha) \cdot \frac{d_{ji}^{t\ell}}{\left(\mathbb{Q}_{ij}^t - k^t B_j^\ell - \Im \right)} \right\}$. In this objective function, the first factor is identical to the objective function of Q-IntraDS, whereas the second factor gives preference to the products that are close to their spoilage limit. Fig. 8(e) shows the effect of mixing with the modified objective function, where α is assumed to be 0.5. From Fig. 8(e) we can observe that the raspberries are given more priority while mixing, due to their higher spoilage rate compared to broccolis.

5   Related Work

Modeling of fresh food spoilage has been considered extensively in the literature. A very recent literature is [Aiello et al., 2012], where the authors have modeled the shelf life of the elegant lady peaches using the time-temperature data, over a linear pipeline of four stages: harvesting, warehousing, transportation, and retailing. Similar approaches for shelf life modeling is discussed in [Park et al., 2013] for chicken breast meat, [Kim et al., 2012] for ground beef, [Bobelyn et al., 2006] for mushrooms etc.

On the other hand, different planning models for agri-food supply chain, starting from farming, harvesting, storing and distribution, is also well-mined. [Ahumada and Villalobos, 2009] provides a thorough review of the state of the art in the area of planning models for the different components of agri-food supply chains for both perishable and non-perishable food products. The perishable food literature, which is of primary interest here, is quite recent and often focuses on specific types of produce. Interestingly as reported in this survey [Ahumada and Villalobos, 2009], the number of works devoted for production-distribution decisions for perishable argi-food supply chain are relatively sparse. In [Rantala, 2004], an integrated production-distribution plan is developed for the seedling supply chain of a Finish nursery company. The main objective of this model is to minimize the total cost of production and transportation while meeting the customer demands as well the capacity related constraints. Authors in [Maia et al., 1997] discuss about the post-harvest handling of fresh vegetables. The purpose of this research is to maximize the expected profit considering the food preservation facilities, under the conditions of uncertain production and demand. These models typically are optimization models and try

to maximize profit or revenue. Reference [Aramyan et al., 2006] presents a conceptual model of supply chain and identifies a number of parameters to quantify the performance of the supply chain network. However, the paper is mostly about defining the metrics and then collecting data for a few case studies. The metrics are classified into four categories that include efficiency, flexibility, responsiveness, and food quality. Efficiency metrics relate to things that the network principals care about (e.g., profit, inventory needs, etc.), flexibility metrics are about how easily the network can adapt to changing environment, responsiveness and food quality mostly deal with customer satisfaction.

Some very recent related works are reported in [Montreuil et al., 2010, Sarraj et al., 2014, Pach et al., 2014] on physical Internet, that proposes the idea of imitating the cyber Internet architecture in physical supply chain. [Lin et al., 2014, Sallez et al., 2015] introduced a mathematical model to select a requisite number of modular containers to pack a set of products to maximize space utilization. In [Pal and Kant, 2016a, Kant and Pal, 2016] the authors have shown that considerable synergies exist between information networks carrying time-sensitive information and perishable commodity distribution networks, and have proposed a five-layer network model to unify the two. Various traceability related issues for contamination detection in logistics system are reported in [Matthews et al., 2014]. To ease traceability in large logistics, the industry has undertaken a *Produce Traceability Initiative* (PTI), which is already implemented by several large food retailers (including Walmart and Whole Foods), and is being adopted by others (See www.producetraceability.org/). The traceability is ensured by diligently implementing two tasks. The first one is to assign unique IDs (barcodes or RFIDs) to each and every entities in the network, and second is to maintain the logs for every individual product that is handled by all the agents. However, these papers talked about some important points regarding reducing empty miles and drivers driving time, standardization of the containers, transportation efficiency, package tracking and traceability etc. while the food quality and freshness have not been discussed.

6   Conclusions

In this paper, we introduced the notion of worker-friendly, $F^2\pi$ architecture and explored the mixing, packaging and delivery of food packages in different parts of the food pipeline. The key characteristics of this proposed architecture is the use of (a) a freshness quality parameter for efficient loading of multiple food products on the trucks and schedule food trucks according to the delivery requirements of individual packages, and (b) infrastructure sharing and efficient transportation to improve the driver's away home time, while maintaining an end-to-end fresh delivery of the food packages. We believe that the proposed $F^2\pi$ architecture will complement the existing efforts of emulating the digital Internet into the traditional logistics networks. However the proposed $F^2\pi$ model requires sharing of various resources (trucks, drivers, warehouses) among different competitive entities/companies, which brings the concern of security, privacy and fairness. In future we want to address the privacy concerns that may arise in such a collaborative and competitive framework.

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