AN APPLICATION OF CROSS-DOCKING THEORY TO SOLVE THE “LAST-MILE LOGISTICS” PROBLEM AT THE PENNSYLVANIA STATE UNIVERSITY’S FOOD DELIVERY DEPARTMENT

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by

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ABSTRACT

The Pennsylvania State University is one of the largest universities in the United States, with huge demands of food to serve the students from all its 24 campuses. As the orders for food are large, the school uses a bulk buying strategy to purchase from the producers, whose prices are 20% to 40% lower than the wholesalers’. The most frequently consumed products are the meat products and the fresh produce (vegetables and fruits). Because the meat products can be frozen to extend their shelf life, the school consolidates orders from all its campuses, and stores the products in the central warehouse located on the University Park (UP) campus. The school’s delivery team then redistributes the products to 15 dining halls and stores on the UP campus as well as all the dining halls on 11 other campuses (the other 12 campuses purchase independently). To save on transportation costs, deliveries are as infrequent as once every two weeks to some campuses. On the other hand, because of the short shelf life of vegetables and fruits, dining halls on campuses outside the UP campus buy from local wholesalers, although the prices are higher. Also, to save time, the suppliers deliver to the dining halls directly (instead of to the warehouse). The transportation costs are high for them because transporting to crowded campuses is very time consuming. This is known as the “last-mile logistics” problem. The handling costs are also high, since the truck from each supplier needs to be unloaded at each dining hall (compare to unloading once at the warehouse).

A cross-docking strategy can be helpful to reduce the costs and by reducing the fuel consumption, it is also helpful to keep the air cleaner. It requires the incoming products being loaded to the outbound trucks directly, to save delivery time and to increase the delivery frequency. By applying this strategy, the school can deliver more frequently to the campuses other than the UP campus to satisfy their demands, consolidating orders to cut out the wholesalers and lowering the purchasing costs. What’s more, the school’s own delivery team can perform the “last-mile logistics” instead of the suppliers, with smaller trucks to save delivery time and costs. There are several ways to apply a cross-docking strategy. Other than the current strategy, three possible alternatives are considered, including pre-allocate cross-docking
strategy, post-allocate cross-docking strategy and hybrid cross-docking strategy. The aim of this research is to compare the total costs under different strategies, and find the one with the lowest cost. A cost comparison model is built in this research that includes three parts: 1) purchasing cost, 2) delivery cost and 3) inventory carrying cost. To optimize the delivery routes with the shortest traveling distances, a vehicle routing problem model is built for the alternative strategies, and the problem is solved by the software LINGO.

By calculating total cost from each strategy, the results show that a hybrid cross-docking strategy is the most suitable strategy, which can save approximately $50,000 annually from the current strategy.
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Chapter 1

Introduction and Overview

1.1 Motivation

This research is motivated by the growing interest in solving the “last-mile logistics” problem. To a freight delivery system, the “last-mile logistics” is the most critical phase. As the name implies, it refers to the last step in a delivery process before the products arrive to their customers. As Goodman (2005) introduced, the Council of Supply Chain Management Professionals estimated that up to 28% of all transportation costs occur in the last mile. This is because the “last-mile logistics” mostly happens in urban areas, where traffic conditions are rapidly changing. The delivery trucks are slowed down, so it becomes more energy and time consuming to the trucks. It is even more challenging to the food delivery system of Penn State University, which currently requires the suppliers of vegetables and fruits for the school to deliver directly to all the 26 dining halls and stores. Because these suppliers use full sized tractor trailer trucks (at least 48 feet in length) to deliver their products, and the bad traffic conditions on the campus such as conflicts with road users, unpredictable pedestrian and bicyclists, etc., it is very time-consuming to drive on the campuses.

The procurement of meats is different. Usually the school applies a bulk buying strategy to purchase from the producers to reduce the purchasing costs. However, the producers only sell in large quantities; if the order is too small, the products can only be purchased from the local wholesalers. As a result, the UP campus consolidates orders from 11 other campuses and procures the items together. These big amounts of goods are stored in the central warehouse at the UP campus, and redistributed by the school’s delivery team when the dining halls and stores need them. However, this policy cannot be applied to vegetables and fruits. As vegetables and fruits always have short shelf life, to maintain
freshness, they cannot be stored in the warehouse for a long time. Each campus of the school can only buy from its local suppliers of these products. Only the UP campus has a big enough demand to buy from the producers; the other campuses buy from local wholesalers.

To allow the school to apply a bulk buying strategy to vegetables and fruits and reduce the “last-mile logistics” cost, a new technique such as cross-docking is required. Cross-docking is a logistics technology that requires the unloaded items to be directly loaded to the outbound vehicles. In the case of Penn State University, with this strategy the vegetables and fruits can be sent to the distribution center first, and redistributed to the dining halls and stores immediately by the school’s delivery team. The new strategy can lower the total handling time, as the products do not need to be put into the warehouse, and items from different suppliers can be delivered at one time. It allows the school’s delivery teams to use regular two-axle trucks to deliver, which are smaller than the tractor-trailer trucks, and running faster on the campus. However, by applying this strategy, the total delivery cost increases as the delivery must be done more rapidly to keep the products fresh.

There are several kinds of cross-docking strategies to serve in different situations, such as pre-allocate cross-docking, post-allocate cross-docking and hybrid cross-docking. We want to compare costs from all these different strategies, and find the one with the least cost.

1.2 Problem Background

Penn State University is a public research university located in Central Pennsylvania. According to Penn State News, the total enrollment for all the 24 campuses including the online World Campus was 98,097 in the fall semester of 2013 (news.psu.edu, 2013). In 2012, the spending in food purchasing was about $40 million for the school. The University Park (UP) campus is the biggest campus among all the campuses, with over 45,500 students. It is also where the Housing and Food Services (HFS) Department and its distribution center are located. The major duty of HFS is to supply cooking and food products for the dining commons and retail stores of the school. It has the function of purchasing, storing, and
redistributing of food products, for 12 campuses. The campuses HFS serves with their relative positions and referral numbers are shown in Figure 1.1. The remaining 12 campuses purchase independently, because their demands are too small and the distances are too far from the UP campus. As the distribution center is on the UP campus, and there are 15 dining halls and retail stores on the UP campus to serve, the distribution center serves on the UP campus more frequently than the others. The other 11 campuses served by HFS are much smaller; each of them only has one dining hall or cafe. HFS uses a bi-weekly schedule to serve them. The delivery frequencies can be from twice a week to once every other week. The actual schedule is shown in Table 1.1 and more details of delivery will be provided later in this chapter.

The current HFS building was built in 1994. The first floor of the building is consisted of a docking area (as the distribution center) and a warehouse (the central warehouse). The building is shown in Figure 1.2.
The upper floors of the building contain several offices for the office workers of HFS to work. The warehouse has three big storage chambers: one chamber at room temperature and two refrigerating chambers. The chamber at room temperature stores foods that do not go bad easily, such as canned food, flour, seasoning, dried noodles, etc. The two refrigerating chambers are mainly for storing meat products. Currently all the meat products purchased by the school are stored here at first. They maintain temperatures below 28 °F, to keep the meat products freezing. All the products are put on huge shelves as shown in Figure 1.3. The three chambers have a total space of over 300,000 cubic feet, and right now they are not filled to capacity, so there is enough room to keep more inventories.
pickers. The receivers unload items from the incoming trucks. Workers to put things away place them onto the shelves. The whole process can be finished in an average of 45 minutes per truck. When the items are needed, the pickers pick up the demanded items from the shelves, and put them onto the outgoing trucks. As the total weight of the items is usually heavy, there are six forklifts to help moving the items. There are 10 docks to dock the trucks; usually there can be one or two inbound trucks and five to six outbound trucks parking together, so that the loading and unloading process can be done at the same time. The school’s delivery team has four drivers with six straight box trucks, one commercial van, and one tractor-trailer truck. Usually, there are three straight box trucks deliver on the UP campus, and one tractor-trailer truck deliver to the other campuses.

The food delivery trucks used on the campus are Ford LCF box trucks. The U.S. Department of Transportation (USDOT) categorizes them as “Non-articulated self-propelled cargo-carrying commercial motor vehicle,” which has a maximum payload of 20,000 lbs., based on the standards of the Interstate Highway System. They are also called straight box trucks for short. According to Ford’s official website, the maximum payload of the truck is 7,000 lbs., and the box’s weight is about 1,000 lbs., making the net maximum payload to be 6,000 lbs. The tractor-trailer trucks are categorized as “Truck tractor-semi-trailer combination” by USDOT, with a maximum payload of 34,000 lbs., based on the standards of the Interstate Highway System. Ravindran et al. (2013) defined a standard full-size tractor-trailer truck to be 53 feet in length, with a width of 98 inches and a height of between 102 to 110 inches. As a result, the total volume of a trailer is 3823 ft\(^3\). Ravindran et al. (2013) assumed the “full” truckload is 80% of the total volume, which is 3059 ft\(^3\). For the straight box trucks, the dimension of the box is 17 feet long, 7.5 feet wide and 8 feet high, making the volume to be 1,020 ft\(^3\). Here we also assume the “full” truckload to be 80% of the total truckload, which is 816 ft\(^3\). As the school planned to increase the number of students enrolled, it planned to purchase another tractor-trailer truck. The schematics of the trucks are shown in Figure 1.4 and 1.5.
The inbound/outbound deliveries are performed every day on the weekdays, dealing with different products. The deliveries on the University Park campus can occur as often as four times per day to different places. In each dining hall there is one receiver to unload. It takes about 30 minutes to unload a truck. Deliveries outside the University Park campus are based on a bi-weekly schedule, and to shorten the distance traveled, they may serve multiple campuses at a time. The relative positions of the campuses can be located in Figure 1.6.
We assume there is only one dining hall or cafe on each campus other than the UP campus. A detailed introduction of the campuses is included in Appendix A. The actual bi-weekly delivery schedule to these campuses is shown in Table 1.1. The first row shows the day of the week, while the first column shows the week. The name of the campus shows which campus is served at the day of the week. Sometimes several campuses are served in the same day, because the campuses are close to one another and the truck’s capacity is enough to carry all the goods. The starting point is always the distribution center and warehouse on the University Park campus, and at the end of each day the trucks must go back to the starting point.

<table>
<thead>
<tr>
<th>WEEK</th>
<th>SUN</th>
<th>MON</th>
<th>TUE</th>
<th>WED</th>
<th>THU</th>
<th>FRI</th>
<th>SAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>Behrend</td>
<td>Altoona Harrisburg/MT Alto</td>
<td>Worthington Scranton &amp; Wilkes-Barre</td>
<td>Hazleton Berks Schuylkill</td>
<td>Altoona Behrend</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Greater Allegheny Beaver</td>
<td>Altoona Harrisburg/MT Alto</td>
<td>Behrend</td>
<td>Hazleton Berks Schuylkill</td>
<td>Altoona</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.1: Delivery schedule from the distribution center

To reduce costs, the HFS purchasing department applies a bulk purchasing strategy, which means purchasing a large amount of items in an order, directly from the producers. The reason is that the
producers would only do business with the school if the order is big enough. For example, the minimum order quantity of yogurt is 300 cases per week; otherwise, the school has to purchase from the wholesalers, whose prices are 20% to 40% higher than the producers’. So to make the order large, the school can consolidate the orders from all the dining halls and stores located on the 12 campuses. But as the vegetables and fruits cannot be stored for a long time, each campus orders them separately.

As there are thousands of different products, it is almost impossible to study all of them. Some of the products are not amenable to the new strategies, and they are not studied. For instance, items such as seasonings have very small demands and low unit prices, so there is no need to apply cross-docking. We do not study items with long product life either, such as flour, because they can usually be easily stored, so the order can be very big. For example, order quantity of flours is for six months’ usage. The order quantity is too big to apply a cross-docking strategy. Dairy products are not considered either, because the creamery’s delivery team delivers them.

We only focus on items with huge or regular demands. According to Pareto’s 80/20 principle introduced by Koch (1998), 20% of products will comprise of 80% of total purchasing, so the study of the regular demanded food can be very representative. The products we want to study can be divided into two categories: meat products and vegetable & fruit products. There are 28 kinds of meat products and 95 kinds of vegetables and fruits are studied in this research. The meat products include raw meats such as chicken breast and chicken wings, and semi-cooked food, such as chicken nuggets and chicken fritters. To get the quantity discount, the HFS always purchases directly from the producers. The items are stored in the HFS warehouse, and then delivered to the dining halls in different campuses. Because of the short product life, they can only be bought in small orders, usually for a 3-day usage. As a result, only the UP campus has the capacity to purchase from the producers; the local wholesalers serve other campuses, as the orders are too small. If the school makes a big order for all these campus, it needs to pay a high transportation cost, which is beyond the savings. The suppliers deliver directly to each dining hall, to save time. Meat product orders are usually made for a 2-week usage.
The purchasing process starts from the dining halls. The chefs decide what dishes to cook for the following months and place orders of the ingredients required. The orders are then sent to HFS’s purchasing office. The office workers consolidate orders from all the dining halls. As there are over 1,000 possible suppliers, the office workers screen them by comparing the prices of the items, and keep several suppliers who have competitive prices. The chefs, who may ask for samples and decide which one to use, make the final decision.

Five main suppliers of meats and another five main suppliers of vegetables and fruits are studied. Vegetables and fruits are delivered twice a week to the dining halls. Meats are delivered by the schedule shown in Table 1.2. The delivery is usually made every other week to the dining halls and stores.

<table>
<thead>
<tr>
<th>Day of a Week</th>
<th>Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monday</td>
<td>C</td>
</tr>
<tr>
<td>Tuesday</td>
<td>B, D</td>
</tr>
<tr>
<td>Wednesday</td>
<td></td>
</tr>
<tr>
<td>Thursday</td>
<td>E</td>
</tr>
<tr>
<td>Friday</td>
<td>A</td>
</tr>
</tbody>
</table>

Table 1.2: Vendor Delivery Day of a Week

The school uses a periodic review policy to order. Instead of setting a reorder point, the purchasing department sets an order quantity for each product and a time interval for the order cycle. The orders are made between the time intervals with the same order quantity.

Not all the dining halls and stores have the same demand. The demands of products are shown in Table 1.3. In the figure, the first column indicates the referral number of the location. The second column indicates the names of the location. The third and the fourth column indicate if the locations require certain kind of item. A Yes means the location needs this kind of product; otherwise it is No.
<table>
<thead>
<tr>
<th>Referral Number</th>
<th>Dining Commons/Retail stores</th>
<th>Require Meat?</th>
<th>Require Vegetables &amp; Fruits?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BJC Catering</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>Blue Chip Bistro</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>Bennett Family Center</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>Cafe Laura</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>Campus Catering</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>6</td>
<td>Findlay Dining Commons / Good 2 Go</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>Hub Dining-Food Court &amp; Kitchen / Sbarro</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>8</td>
<td>Mount Nittany Club</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>9</td>
<td>Pollock Commons/The Mix)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>10</td>
<td>Redifer Commons / Louie’s</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>11</td>
<td>Schultz Child Care Center at Hort Woods</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>12</td>
<td>Waring Commons / Sisu</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>13</td>
<td>Warnock Commons</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>14</td>
<td>Nittany Lion Inn</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>15</td>
<td>Penn Stater</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 1.3: Table of dining commons & retail stores served on the University Park campus

The campus map of the University Park campus is shown in Figure 1.7. In the figure, the star shows the position of the central distribution center and warehouse. The circles indicate the positions of the dining halls or stores. The names of the locations are indicated in the blocks.
1.3 Contribution

This research has three main areas of consideration by applying cross-docking: 1) consolidate orders to apply bulk buying strategy and cut out the wholesalers, 2) reduce handling time and handling costs, and 3) redesign the delivery routes to lower the delivery costs. The aim of the research is to reduce the total cost without increasing the handling time and inventory turnover time in the current situation.

Cross-docking is a relatively new topic. It is widely used by retail stores such as Wal-Mart, and it helps Wal-Mart to achieve a huge success logistics. However, the application of cross-docking in a school has not been researched. There are some articles online discussing cross-docking of food products, such as the article by Vasiljevic et al. (2013), which presents the case of a food delivery system for some retail stores in Serbia, and the article by Apte et al. (2000), which introduces applying cross-docking in the
delivery of chilled food in a general scope. However, no article online discusses cross-docking of food in a university. Universities are an important market for the food industry, because of the huge and steady demands from students, making its food delivery system different from the retail stores. The main savings by applying cross-docking in a retail store are from reducing delivery times and inventory carrying costs, as this enables rapid reaction to the unpredictable demands. In the case of Penn State University, the main savings are from the purchasing costs, because cross-docking enables the school to apply a bulk buying strategy for vegetables and fruits. Although the managers of the Housing and Food Service department would like to apply cross-docking strategies, they are not sure whether this new strategy can save money or not. This is because cross-docking requires inbound goods to be directly loaded to the outbound vehicles, which requires additional labor to sort and consolidate the goods and additional vehicles to increase frequency of delivery, as there is no storage space. As a result, currently the school only applies cross-docking to a small number of products, such as yogurt and juice, in order to see how beneficial the new strategy can be.

Obviously, cross-docking strategy can help to save handling times and inventory carrying costs, so we do not consider time as an objective. Instead, we use “cost” as the objective. We present four scenarios with possible delivery strategies, include the current strategy and three alternative strategies: pre-allocate cross-docking strategy, post-allocate cross-docking strategy and hybrid cross-docking strategy. A cost-comparison model is built to compare the purchasing costs, delivery costs and inventory carrying costs in the scenarios. We design the delivery routes outside the UP campus in the alternative strategies, which is a typical vehicle routing problem (VRP). We use LINGO to solve the VRP. LINGO is a software program to solve linear, nonlinear and integer optimization models. By using LINGO we can find the optimal delivery routes with the shortest total traveling distance. After determining the optimal routes, the comparison model is used to find the costs of the strategies. In the end we can compare the total costs and determine the one with the lowest cost. We use real world data obtained from the Housing and Food Service Department of Penn State University, so the result is able to predict the real world situation.
Cross-docking enables the school to deliver vegetables and fruits by its own delivery team using smaller trucks to reduce the “last-mile logistics” costs. Also, as the orders are consolidated, the vegetables and fruits can be purchased together. Therefore the school can use a bulk buying strategy to cut out the wholesalers. Although the total delivery cost increases, it can be covered by the savings in the purchasing costs.

The managers of the school’s food purchasing department can use this model to determine the costs of a new strategy in the future. Also, the LINGO model is very helpful in choosing the delivery routes. It is also possible for the managers to find the potential benefits in purchasing for more campuses of the school.

1.4 Overview

This thesis paper is organized as follows.

Chapter 2 presents a literature review. The articles that inspired this research topic are introduced here. The articles providing essential methods in finding the solution of the problem are also introduced here.

Chapter 3 introduces the models built for solving the problem based on the theories presented in chapter 2.

Chapter 4 applies the models to the real world problem in the Pennsylvania State University. Real data is used in this part to obtain an accurate result and prove the hypothesis of the research. It summarizes the results from the calculations.

Chapter 5 presents the conclusion and future work. As a conclusion, the hybrid cross-docking strategy is recommended for the food delivery system of Pennsylvania State University, to help save time and money.
Chapter 2

Literature Review

This chapter reviews the previous relevant research work, which is the motivation to this thesis’ research. Section 2.1 introduces previous implementations of cross-docking in real world applications. These successful examples inspired us to apply cross-docking at the Penn State University’s food delivery system. Section 2.2 presents a general introduction to warehousing and the related logistics strategies. Section 2.3 introduces several types of cross-dockings. Section 2.4 introduces the purchasing cost model. Section 2.5 introduces some common inventory holding strategies. Section 2.6 introduces the vehicle routing problem (VRP), which affects the transportation cost of a distribution system. Section 2.7 introduces some studies in the “last-mile logistics” problem.

2.1 Empirical Studies of Cross-docking

The idea of applying cross-docking in food distribution has already been researched before, for example, Vasiljevic et al. (2013) provided an application of cross-docking in the distribution of agriculture products. The researchers studied the distribution system of agricultural products from a large retail chain in Serbia. Before applying cross-docking, a central distribution center located in Belgrade served all the stores of the retail chain, including 21 retail stores in another area called Vojvodina, which is about 75 miles away from Belgrade. 7 trucks were needed to deliver agriculture products from Belgrade directly to the stores in Vojvodina every day. The researchers decided to apply cross-docking to the retail chain to reduce the costs. A new strategy was developed as placing a new cross-docking center in Vojvodina. Trucks from the Belgrade delivered goods to the cross-docking center, from where 3 trucks were used to redistribute the goods to the 21 retail stores. Based on the study, cross-docking shortened the handling time and the total traveled, and lowered number of trucks required. The conclusion of the study
demonstrated that cross-docking could save about $14,000 per year for the retail chain. The main savings were from fuel consumptions, value of time spent, maintenance costs and lease costs. Thus, the researchers concluded that cross-docking could achieve significant savings for the retail chain of agricultural products.

Cross-docking requires both an intensive understanding of the system and a deliberate plan. Weche (2012) gave more details about how to apply cross-docking in a logistics system. He worked on the case of setting up a fast-moving supply network in Western Europe for Procter & Gamble. He focused on the process from the wholesaler to the retailers’ distribution center, and the process from the retailers’ distribution center to the retailers’ stores. He set up several models for different scenarios, including applying the current strategy, pre-allocating cross-docking strategy, and post-allocating cross-docking strategy. In the end, he applied real-world data to the models and calculated the total costs. Based on his study, cross-docking worked much better than the current strategy as the volume of products was high. If the volume was low, savings from the inventory holding cost could not cover the extra delivery cost. So the total cost would be higher than the current storage method.

2.2 Warehousing

As introduced by Koster et al. (2006), the cost of warehousing contributed approximately 20% of a company’s logistics costs in 2003. Even though warehousing is costly, most companies cannot eliminate this step from their logistics systems. Lambert et al. (1998) defined the contributions of warehousing as:

1) Achieving transportation and production economics
2) Taking advantage of purchasing discounts
3) Meeting changing market conditions
4) Overcoming time and space differences between products and customers
A typical warehouse performs the functions of receiving, storing and shipping, as shown in Figure 2.1. The arrows indicate the movements of products, and the rectangles indicate the processes. Koster et al. (2006) defined warehouse flows to start from the receiving activity including, unloading of products, updating inventory record, etc. Then the products are transferred and put away into storage locations, which may also include repackaging and movement through other functional areas. If there is an incoming order, the order picking step starts, based on customers' orders. After the order picking, the products are usually packed and stacked, awaiting shipment. In this research, this warehousing strategy is called the traditional strategy, because it is the most popular warehousing strategy currently being used.

Figure 2.1: Typical warehouse function and flow (adopted from Tompkins et al. 2003)

The benefit of this strategy is obvious: the warehouse performs as a buffering station, giving the system the ability to deal with floating demands. It also enables a company to apply bulk buying strategy, as the extra commodities can be put in the warehouse. The drawback is also very obvious: it can be costly to hold the inventory. A high inventory level can reduce the operational capital of a company, while increasing the risks of inventory being stolen and broken.
### 2.3 Cross-docking Strategies

Cross-docking is a logistics technique with no storage, but rather direct distribution of the incoming products from the suppliers or manufacturers to the customers or retailers (Bartholdi et al., 2004). Items in big orders are sent to a cross-docking terminal from the suppliers or manufacturers, to be broken down into smaller orders. A cross-docking terminal usually has multiple docks to let the inbound and outbound vehicles park at the same time. Items unloaded from the inbound vehicles will be sorted in the docking area and temporarily stored, usually for less than 24 hours, and then they will be loaded to the outbound vehicles to the customers or retailers. There are several advantages of cross-docking over the traditional logistics strategy. As there is no need to store and pick items, applying cross-docking can reduce the handling costs. Because there requires no inventory, the inventory holding cost can be significantly reduced too. Figure 2.2 shows the idea of cross-docking. There is no warehouse, but a cross-docking terminal. The arrows show the moving directions of items.

![Cross-docking process](image)

**Figure 2.2: Typical cross-docking process**

A cross-docking terminal performs the functions as a distribution center. Tang (2007) defined a cross-docking terminal’s functions as receiving goods, sorting goods and shipping goods. It is usually the middle point between suppliers and retailers. Figure 2.3 shows a typical cross-docking flow. As shown in
the diagram, there is no storage step. Without applying cross-docking, as an order from a single retailer is always too small to fill a truck, to save the transportation cost, a less than truck load (LTL) delivery strategy is often applied by the supplier. Tang (2007) defined LTL as one truck carrying items from several different customers. The same truck can deliver items ordered by different retailers from a supplier. To save time, the items are usually delivered directly to the retailers. On the other hand, a cross-docking strategy requires a distribution center to receive and sort the items. It enables a full truck load (FTL) delivery strategy at the distribution center. Tang (2007) defined FTL as a truck carrying items demanded by a single customer. Items from different suppliers will be sorted based on destinations, so an outbound truck carries different items to the same destination. If the orders are small, it is possible that items for several retailers are delivered together. Because each truck stops less times, this strategy can lower the handling costs, reduce the delivery time, and may shorten the total traveling distances.

![Diagram of distribution facility process](image)

Figure 2.3: Process in distribution facility (adopted from Tang, 2007)

There are different kinds of cross-docking strategies to serve different situations. Schaffer (2000) defined three types of cross-docking: manufacturer cross-docking, retailer cross-docking and distribution center cross-docking. The classification is based on where cross-docking is carried out, as indicated by their names. Another way to classify cross-docking is based on who has the duty of sorting and preparation work. Gue (2001) introduced two types of cross-docking: pre-distribution cross-docking and post-distribution cross-docking. Pre-distribution cross-docking is also called pre-allocate cross-docking, which requires the supplier to prepare and sort items before shipping. The works include attaching labels, pricing items, sorting items according to the retailers’ demands, etc.

By applying a pre-allocate cross-docking strategy, orders from the retailers can be directly sent to the suppliers. Each supplier groups different items based on the orders, and loads them to their outbound
trucks to the distribution center. Once the items arrive at the cross-docking terminal, the workers only need to move the items to the outbound trucks, based on destinations. The flow is shown in Figure 2.4. The small rectangles indicate three different products in three different colors; circles with number 1, 2, and 3 indicate three retail stores; the triangle indicates the supplier. As we can see, the items have already been assigned to different stores before arriving at the cross-dock facility.

![Pre-allocate Cross-docking Strategy](image)

Figure 2.4: Pre-allocate Cross-docking Strategy (adopted from warehows.wikispaces.com, 2013)

The advantage of this strategy is that it can save a great deal of work in the distribution center. On the other hand, there will be more works for the suppliers, so the suppliers may charge more. Therefore, companies with few suppliers but huge demands often apply this strategy. It can also be used by companies that produce and sell (act as supplier and distributor), such as P&G.

To the contrary, a post-distribution cross-docking (post-allocate cross-docking) requires the distribution center to prepare and sort the items. Orders from different retailers are usually consolidated and sent to the supplier. The supplier sends the items to the cross-docking terminal without sorting. At the cross-docking terminal, the items will be unloaded and stored at the temporary storage area, which is usually a free space at the dock. The items are assigned to different retailers based on the orders. Kulwiec
(2004) presented two different ways from this point: with an order balancing process, the items assigned to the same retailer will be consolidated and loaded to the same outbound truck later; without an order balancing process, the incoming items will be shipped to each retailer as soon as possible. The flow is shown in Figure 2.5, where CDO means cross-docking operator. The small rectangles with different colors indicate different items; circles with number 1, 2 and 3 indicate the retailers; the triangle indicates the supplier. As we can see, the items are grouped by item types from the supplier. They are assigned to different retailers at the cross-dock facility and shipped.

The advantage of this strategy is that the suppliers do not need to change their shipping methods. However, extra works happen in the cross-docking terminal. A company who needs to purchase from numerous different suppliers, such as Wal-Mart, usually applies this method.

In some situations, there may be some restrictions to apply cross-docking. For example, if it is hard to forecast the demand, a company has to keep some inventories as safety stock. In this concern,
some companies choose to apply another cross-docking technique called hybrid cross-docking. Kulwiec (2004) presented the idea of hybrid cross-docking, which can also be called blended cross-docking. Unlike the pure cross-docking strategies (pre-allocation cross-docking and post-allocation cross-docking), there is a warehouse at the cross-docking terminal that keeps a certain level of inventory. Once the items from inbound trucks cannot meet the orders from the retailers, the distribution center can fulfill the demands by blending the incoming items with items from the storage. The cross-docking terminal may also find substitute suppliers or even manufacturers to get the additional products. On the other hand, if the retailers ordered more than they need, the extra items can be stored in the warehouse. The flow is shown in Figure 2.6, where both a cross-docking terminal and a warehouse exist.

Figure 2.6: Hybrid Cross-docking Strategy (adopted from www.brainsins.com, 2012)

In this strategy, it combines cross-docking and the traditional logistics techniques. It lowers the handling costs and time, and has some ability to deal with floating demands. However, the advantages from each method are not very significant as they were. In a word, hybrid cross-docking strategy is a strategy between cross-docking and traditional strategy, with both in the good parts and bad parts. It can
be quickly adapted into almost any situation by balancing the ratio of cross-docking and traditional storage.

2.4 Purchasing Cost Model

Ghodsypour et al. (2001) presented a decision support system (DSS) to help reducing the number of suppliers. They developed a single objective model to perform supplier selection with multiple sourcing, multiple criteria and discounted price. They also considered the effects of limitations on budget of buyers, product quality and suppliers’ capacity. In their model, the total annual purchasing cost (TAPC) includes three parts: annual ordering cost (AOC), annual holding cost (AHC) and annual purchasing cost (APC). The annual ordering cost indicates the cost of placing orders. Ordering cost is a fixed cost in every order, so the annual ordering cost was expressed as the unit ordering cost multiplied by the number of orders in a year. The annual holding cost describes the yearly cost of keeping items in inventory. To simplify the calculation, Ghodsypour et al. (2001) expressed the annual holding cost to be equal to the average inventory level multiplied by the unit holding cost. However, in reality, the annual holding cost is more complicated to calculate. Therefore, more completed models to calculate the inventory holding cost are presented in Section 2.5. The annual purchasing cost is simply calculated by multiplying the annual order quantity and the unit price. Although this model is simple, it can be used to compare the total purchasing costs between situations with different demand, minimum acceptable perfect rate, budget and order allocations.

2.5 Inventory Carrying Strategies

Myerson (2012) introduced the concepts of lean supply chain as well as how to become more “lean” in the supply chain network. He defined the core idea of “lean” to be identifying and eliminating waste. In reality, the process of storing is not as simple as putting items away and getting items out. There
are always extra actions, such as moving items from one place to another on the floor, travel between racks, etc. There is also a risk of losing and damaging items. For most companies, keeping additional inventory can be a buffer to meet the customer demands; however the inventory levels are usually higher than needed, and can cause wastes in labor and capital. As we know, the safety stock level is affected by the variability of the supply chain system. Myerson (2012) believed that the managers should identify the variability first, and then use analytical tools to reduce the variability, so that the inventory level drops.

Bowersox et al. (2012) introduced more about inventory carrying problems. The inventory carrying cost describes the cost of maintaining commodities as inventory. As the exact spending on each item in a warehouse is very difficult to find, an alternative solution is used. Bowersox et al. (2012) presented that the inventory carrying cost is usually calculated as a percentage of the purchase or standard manufacturing cost in standard accounting practice. This is because the inventory level is relatively stable, so an average inventory level can be found. The inventory carrying cost is calculated based on that average cost. The inventory carrying cost usually consists of five parts: capital, taxes, insurance, obsolescence and storage. Their weight percentages in the total inventory cost are shown in Figure 2.7. Here, all the percentages are based on the total purchasing value. The total inventory cost is assumed to be 15% of the purchasing value of the inventory, and the area of each part stands for the weight of the part in the inventory cost.

![Figure 2.7: The combination of inventory carrying costs](image_url)

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Ravindran et al. (2013) introduced two common inventory strategies. The first one is Continuous Review strategy, or (Q,R) Inventory strategy. It requires a warehouse to keep a certain level of inventory, which is S, in number of cases. The inventory level are continuously watched; once the inventory level becomes lower than the reorder point R, it places another order with order quantity Q. Kallenberg (1997) introduced the central limit theorem. According to the central limit theorem, as the individual demand during the lead-time is random, the total demand is normally distributed. It is assumed that the values of demand during lead-time are normally distributed, with a mean of $\mu_{LTD}$ and a variance of $\sigma^2_{LTD}$. Assume there is no back order allowed here, the basic equation for total annual cost (TAC) is:

$$TAC(Q, R) = A \frac{D}{Q} + H \left( \frac{Q}{2} + R - \mu_{LTD} \right)$$

(2.1)

where $Q$ is the order quantity. $R$ is the reorder point. $A$ is the set-up cost, which is usually a fixed cost occurred at each order. $D$ is the demand rate, in quantity per unit time. $H$ is the holding cost per unit time per item. $\mu_{LTD}$ is the average demand during the lead-time, in quantity per unit time.

As shown in Figure 2.8, the inventory level is shown as the bold lines, x axis stands for time while y axis stands for inventory level. $Q$ is the order quantity, $R$ is the reorder point and $L$ is the lead-time, which describes the time between order placement and items arrive. $T$ is the cycle time, which is the time between two order placements.
The other inventory strategy is Periodic review policy which can be represented by a “reorder point order up to” model defined by Ravindran et al. (2013). In this strategy, the product level will be reviewed periodically. If the inventory level is lower than the predetermined level $S$ in numbers of cases, an order will be placed to bring the inventory level to $S$. The basic equation is similar to the continuous review policy:

$$TAC(T, S) = A \frac{D}{Q} + H \left( \frac{S - SS}{2} + SS \right)$$ (2.2)

where $T$ is cycle time, $S$ is maximum inventory level, $A$ is set-up cost, $D$ is demand rate, $Q$ is order quantity and $H$ is average holding cost. $SS$ is safety stock level, which is the extra inventory to deal with floating demands.

As shown in Figure 2.9, the bold line is the inventory level, x axis stands for time while y axis stands for inventory level, $R$ is reorder point, $S$ is maximum inventory level, $L$ is lead-time, $T$ is cycle time and $SS$ is safety stock.
2.6 Vehicle Routing Problem

A vehicle routing problem (VRP) refers to the distribution problem in which the delivery vehicles are required to serve several customers based at a central depot. Filipec et al. (1998) introduced a basic model to calculate a VRP. Lee et al. (2006) solved the vehicle routing problem as a data envelopment analysis (DEA) problem. A mathematical model was built to modify a supply chain network with a central distribution center, using LTL strategy. As shown in Figure 2.10, CD stands for Cross Dock, which is the central distribution center. The arrows indicate the paths of vehicles, while the circles indicate the nodes. Because this is a closed loop problem, by the end of the day the vehicles must go back to the distribution center.
Figure 2.10: A supply chain network for cross-docking (adopted from Lee et al., 2006)

As the routes of delivery greatly influence the transportation costs, before calculating the transportation costs we must first solve the VRP. As mentioned by Lee et al. (2006), the software LINGO can be used to solve such a problem, which is used in this research.

There are two constraints to be considered when designing the delivery routes: volume of trucks and weight capacity of trucks. Ravindran et al. (2013) defined a standard full-size tractor trailer truck to be 53 feet in length, with a width of 98 inches and a height of between 102 to 110 inches. As a result, the total volume of a trailer is 3823 ft$^3$. Ravindran et al. (2013) assumed the “full” truckload is 80% of the total volume, which is 3059 ft$^3$. The maximum loading capacity of a trailer truck is 34,000 lbs based on the U.S. Federal Government’s regulations.

2.7 Last-mile Logistics

According to Goodman (2005), “Last-mile Logistics” refers to the final transportation piece in a product’s supply chain, and usually describes the last mile transportation before a product reaches its customer. Although the travel distance is usually short, this approach accounts for as much as 28% of all the transportation costs. The reason for such a cost is usually because of the traffic congestion. According to Reisman (2011), 80% of last-mile logistics are performed by trucks. As a truck takes more space and moves slowly, it always increases the congestion. Also, because of the “noise, visual intrusion, physical
intimidation (of pedestrians and cyclists) and traffic accidents” (Allen et al., 2010), the transportation in the urban area costs even more. What is more, because last-mile logistics is the last step to placing a product in a customer’s hand, it affects the customer’s experience directly, which can also affect the revenue of the company. Recently, there are more and more companies paying attention to last-mile logistics.
Chapter 3

Methodology

3.1 Problem Statement and Objectives

This chapter introduces the development of a mathematical model to analyze the food delivery system at Penn State University. The main objective is to minimize the cost, with three main concerns:

1) The delivery cost of vegetables & fruits on the University Park (UP) campus can be reduced
2) The unit-purchasing price of vegetables & fruits can be reduced by cutting out the wholesalers
3) The handling time and inventory holding time can be reduced

The first concern of this research is to lower the last-mile logistics cost on the UP campus. The solution is to use the school’s own delivery team to deliver on the campus directly to the dining halls. To save the handling time, a cross-docking strategy can be used. This research will find out how much money can be saved after using cross-docking.

Secondly, a cross-docking strategy can be used to increase the frequency of deliveries to the campuses outside the UP campus. The school can consolidate the orders of vegetables and fruits, and cut out the wholesalers to reduce the purchasing cost. An assessment is done to compare the costs before and after applying cross-docking.

Thirdly, as cross-docking requires no inventory in the distribution center, the inventory holding cost reduces. There is no storing process, so the handling cost is reduced.

Two kinds of products are considered in this research: meat products, and fresh produces (vegetables and fruits). Currently, the delivery strategies vary for different products. The meat products, which include both fresh and frozen meat products, are all delivered to the central warehouse located on the UP campus. The vegetables and fruits are delivered directly to the dining halls, cafes and stores.
(which are all called “dining halls” in the following chapters) of the 12 campuses. Not all the dining halls require both products.

Other than the current strategy, we have three alternative strategies that can be applied. Therefore, there are four scenarios. The first scenario is for the current strategy. There are three scenarios to perform cross-docking strategies: pre-allocate, post-allocate and hybrid cross-docking. Pre-allocate strategy requires the supplier to allocate the goods before delivering to the distribution center, while post-allocate requires the distribution center to allocate the goods and deliver them to the dining halls. The last scenario is hybrid cross-docking, which is a combination of the traditional strategy and cross-docking. In each scenario we have three main costs to be calculated:

1) Annual purchasing cost
2) Annual delivery cost
3) Annual inventory carrying cost

The delivery routes need to be redesigned for the alternative strategies. This is known as the vehicle routing problem. By solving the vehicle routing problem, an optimized travel route can be found to minimize the total traveling distance. Because of the long distances from the University Park campus to the other campuses (from 60 miles to 200 miles), the optimized delivery routes can save a great deal in the transportation costs. A vehicle routing problem is not considered for the delivery on the University Park (UP) campus. The total transferring distance between the dining halls is only about 5 miles, so different routes make little changes to the total delivery costs. The delivery routes on the campuses outside the UP campus are not considered, because only 1 dining hall in each of them.

The dining halls on the UP campus are assumed to be identical, that is, the delivery processes and times are same. To the other campuses, there is only 1 dining hall in each of them, which means the products will be directly delivered to the warehouse of the dining halls. We assume all the dining halls outside the UP campus are the same.
3.2 Data Description

To prove the effects of applying cross-docking and solve the real-world problem, some real world data is collected. The data is the inbound and outbound products’ information, given by the Housing and Food Service department of Penn State University. It includes information of vegetables, fruits and meat delivered into and out of the central warehouse on the UP campus, for a typical month. The category of fields includes product name, inbound date, vendor, inbound quantity, outbound date, destination, and outbound quantity. It includes 95 kinds of vegetables and fruits from five different vendors, and 28 kinds of meats from another five different vendors. A sample of the data is shown in Appendix D. Although there is only data for one month, it can represent the average level for a normal school day. This is because the number and flow of students eating in the dining halls are very steady, which make the demand of food steady, too. The prices of the products are obtained from the official website of U.S. Department of Agriculture and from FoodServiceDirect.com.

3.3 Research Process

After collecting the data needed, a step-by-step process is applied to complete the research:

1) Calculate the annual total cost in the current situation.
2) Design delivery routes in the alternative strategies
3) Calculate the annual total costs of the alternative strategies.
4) Compare the costs and determine the least costly strategy.

3.4 Model Setting

In this section, the mathematical model is introduced. Before describing the model, the following notations are defined:
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i, j$</td>
<td>Location indices, indicate where a handling process happens or where the items go to. When $i$ and $j$ appear together, it means traveling from $i$ to $j$.</td>
</tr>
<tr>
<td>$g$</td>
<td>Location index, indicates a mid-point between $i$ and $j$</td>
</tr>
<tr>
<td>$[i]$</td>
<td>Location index indicating delivery sequence in a route</td>
</tr>
<tr>
<td>$f$</td>
<td>Item index</td>
</tr>
<tr>
<td>$h$</td>
<td>Supplier index</td>
</tr>
<tr>
<td>$m$</td>
<td>Truck index</td>
</tr>
<tr>
<td>$k$</td>
<td>Stage index</td>
</tr>
<tr>
<td>$d$</td>
<td>Delivery route index</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of different items</td>
</tr>
<tr>
<td>$e$</td>
<td>Number of trucks being used</td>
</tr>
<tr>
<td>$r$</td>
<td>Number of delivery routes</td>
</tr>
<tr>
<td>$y_h$</td>
<td>Annual number of orders from supplier $h$</td>
</tr>
<tr>
<td>$a_h$</td>
<td>Set up cost of supplier $h$, in dollars</td>
</tr>
<tr>
<td>$p^f_h$</td>
<td>Unit price of item $f$, purchased from supplier $h$, in dollars per pound</td>
</tr>
<tr>
<td>$t^k_i$</td>
<td>Working time of stage $k$ at location $i$, in hours</td>
</tr>
<tr>
<td>$b$</td>
<td>Number of suppliers of vegetables and fruits as producers</td>
</tr>
<tr>
<td>$c$</td>
<td>Number of suppliers of vegetables and fruits as local wholesalers</td>
</tr>
<tr>
<td>$l$</td>
<td>Number of suppliers of meats</td>
</tr>
<tr>
<td>$wc$</td>
<td>Weight capacity of a truck</td>
</tr>
<tr>
<td>$md$</td>
<td>Maximum allowed route distance for a day</td>
</tr>
<tr>
<td>$pg$</td>
<td>Unit price of fuel, in dollars per gallon</td>
</tr>
<tr>
<td>$dl$</td>
<td>Driver’s unit labor cost, in dollars per hour</td>
</tr>
<tr>
<td>$wl$</td>
<td>Worker's unit labor cost, in dollars per hour</td>
</tr>
<tr>
<td>$nw^k_i$</td>
<td>Number of workers working at location $i$ at stage $k$</td>
</tr>
<tr>
<td>$nd^m$</td>
<td>Number of truck drivers in truck $m$ (usually $nd^m = 1$)</td>
</tr>
<tr>
<td>$ds_{i,j}$</td>
<td>Distance from location $i$ to location $j$, in miles</td>
</tr>
<tr>
<td>$ds_{[i-1],[i]}$</td>
<td>Distance from location $[i-1]$ to location $[i]$, in miles</td>
</tr>
<tr>
<td>$tt_{[i-1],[i]}$</td>
<td>Traveling time from location $[i-1]$ to location $[i]$, in hours</td>
</tr>
<tr>
<td>$tr^m$</td>
<td>Truck $m$’s fuel cost rate, in miles per gallon</td>
</tr>
<tr>
<td>$tf^m$</td>
<td>Truck $m$’s unit fuel cost, in dollars per mile</td>
</tr>
<tr>
<td>$tm^m$</td>
<td>Truck $m$’s unit maintenance cost, in dollars per mile</td>
</tr>
<tr>
<td>$f^m$</td>
<td>Forklift’s unit maintenance cost, in dollars per hour</td>
</tr>
<tr>
<td>$fc$</td>
<td>Forklift’s unit energy cost, in dollars per hour</td>
</tr>
<tr>
<td>$nf^k_i$</td>
<td>Number of forklifts used in stage $k$ at location $i$</td>
</tr>
<tr>
<td>$ss^f_{ih}$</td>
<td>Average safety stock level of item $f$ at location $i$ from supplier $h$, in pounds</td>
</tr>
<tr>
<td>$cr$</td>
<td>Average inventory carrying cost rate, as a percent</td>
</tr>
<tr>
<td>$x_{i,j}^d$</td>
<td>Binary variable. $x_{i,j}^d = 1$ indicates the truck travels from location $i$ to $j$ in route $d$; otherwise $x_{i,j}^d = 0$. $i \neq j$</td>
</tr>
<tr>
<td>$DR_h$</td>
<td>Discount rate in purchasing cost from supplier $h$, as a fraction</td>
</tr>
<tr>
<td>$Z_{d,m}^d$</td>
<td>Annual number of deliveries in route $d$ by truck $m$</td>
</tr>
<tr>
<td>$IO_h$</td>
<td>Set of items ordered from supplier $h$</td>
</tr>
</tbody>
</table>
\[ ID_i \] \quad \text{Set of items delivered to location } i \\
\[ I \] \quad \text{Set of locations on the UP campus} \\
\[ I^d \] \quad \text{Set of locations visited during the delivery on the UP campus in route } d \\
\[ J \] \quad \text{Set of locations outside the UP campus} \\
\[ J^d \] \quad \text{Set of locations visited during the delivery outside the UP campus in route } d \\
\[ M \] \quad \text{Set of trucks} \\
\[ K \] \quad \text{Set of stages during the delivery process} \\
\[ D \] \quad \text{Set of delivery routes} \\
\[ OC_h \] \quad \text{Ordering cost from supplier } h \text{ for one order, in dollars} \\
\[ DC_{im} \] \quad \text{Delivery cost of truck } m \text{ to location } i \text{ for one time, in dollars} \\
\[ DC_{d,m} \] \quad \text{Delivery cost of truck } m \text{ to deliver in route } d \text{ for one time, in dollars} \\
\[ HC_{ik,m} \] \quad \text{Handling cost of truck } m \text{ at stage } k \text{ at location } i \text{, in dollars} \\
\[ TC_{im} \] \quad \text{Transportation cost of truck } m \text{ to location } i \text{, in dollars} \\
\[ TC_{d,m} \] \quad \text{Transportation cost of truck } m \text{ in route } d \text{, in dollars} \\
\[ Q^f_h \] \quad \text{Order quantity of product } f \text{ from supplier } h \text{, in pounds} \\
\[ Q^f_{i,h} \] \quad \text{Order quantity of product } f \text{ by location } i \text{, from supplier } h \text{ in pounds} \\
\[ Q_j \] \quad \text{Order quantity of products delivered to location } j \text{ in one order, in pounds} \\
\[ DS^d \] \quad \text{Total traveling distance in route } d \\

Table 3.1: List of parameters and variables

Assume the stage index \( k \in K, K = \{1, 2, 3, 4, 5\} \). These stages are the critical steps during the delivery process. The definitions are shown in Table 3.2.

<table>
<thead>
<tr>
<th>Index ( k )</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unloading at the distribution center</td>
</tr>
<tr>
<td>2</td>
<td>Put goods into the warehouse</td>
</tr>
<tr>
<td>3</td>
<td>Pick goods out of the warehouse</td>
</tr>
<tr>
<td>4</td>
<td>Load onto the outbound truck</td>
</tr>
<tr>
<td>5</td>
<td>Unloading at the dining halls</td>
</tr>
</tbody>
</table>

Table 3.2: Definitions of stage indices

We redefine Ghodsypour et al. (2001)’s total annual purchasing model, and present the total annual cost (TAC) model. TAC equals the sum of all the costs occur during the purchase of goods and keeping them good in inventory. The main costs are purchasing cost, delivery cost and inventory carrying cost. So TAC can be stated as:

\[
\text{TAC} = \text{annual purchasing cost (APC)} + \\
\text{annual delivery cost (ADC) + }
\]
annual inventory carrying cost (AICC)

There are two kinds of suppliers: the producers and the wholesalers. Prices offered by the producers are lower than those offered by the wholesalers for the same products. Therefore, by cutting off the wholesalers, the purchasing cost is lowered. Delivery cost is usually a part of the purchasing cost. The suppliers offer higher prices if they deliver. We are unable to get the price information from the suppliers of the school, however, if the school’s delivery team delivers, the prices are lower for the savings of delivery cost. In this case, the demand of each item is very stable, so we consider the delivery cost as an independent cost, which can be calculated. Then we compare the differences in delivery costs between different strategies, and try to find the least costly one. In the end, the savings by the new strategy from the current strategy is converted into a price discount from the supplier. For the campuses outside the UP campus, we assume that there is only one dining hall in each campus, and the deliveries are directly to those dining halls.

The costs are defined in the following sections.

3.4.1 Annual Purchasing Cost (APC)

As long as supplier $h$ is chosen to purchase from, an ordering cost occurs. Although the suppliers of vegetables and fruits are different from the suppliers of meats, all of them have the same ordering cost structure. The expression of $OC_h$ is:

$$OC_h = a_h + \sum_{f \in IO_h} (p_h^f \times Q_h^f) \times (1 - DR_h)$$  (3.1)

where $a_h$ is the set up cost when purchasing from supplier $h$. It occurs whenever an order is placed, and it is a fixed cost to all the orders from the same supplier. In the alternative strategies, we do no change to the order frequencies, but there are changes to the order quantities, therefore order quantity is a variable. Type of goods ordered from supplier $h$ is $IO_h \in \{1, 2, ..., n\}$. If the order quantity is big, the goods can be purchased from producers; if the order quantity is not big enough, the goods can only be purchased from
local wholesalers, which offer higher prices. $DR_h$ is the discount rate in the purchasing cost from supplier $h$. If a supplier delivers to the distribution center instead of the dining halls, it can reduce its delivery costs. The savings can be converted into a discount in the purchasing cost of the items. So

$$DR_h = \frac{savings\ in\ delivery\ cost}{purchasing\ cost}$$ to a supplier $h$. $(1 - DR_h)$ is the portion of cost after applying the discount.

By considering the annual number of purchases from all the suppliers, APC can be expressed as:

$$APC = \sum_{h=1}^{b+c+l} (OC_h \times y_h)$$

(3.2)

$y_h$ is the annual number of purchasing orders from supplier $h$. Because the demands are stable, we assume $y_h$ is a fixed number to each supplier. There are two types of suppliers for vegetables and fruits, as producers and wholesalers. $b$ is the number of producers for vegetables and fruits to the school, and $c$ is the number of wholesalers for vegetables and fruits. $l$ is the number of suppliers of meats, which are all producers.

### 3.4.2 Annual Delivery Cost (ADC)

Delivery costs refer to costs of delivering goods on the campus and between the campuses. Trucks are used to deliver the goods, and a single truck usually carries more than one type of good, so we calculate delivery costs based on trucks. Also, a truck travels in different routes cost differently, so we distinguish which route a truck follows. The equation to calculate ADC is:

$$ADC = \sum_{d \in D} \sum_{m \in M} (DC^{d,m} \times Z^{d,m})$$

(3.3)

In this equation, $DC^{d,m}$ is the one-time delivery cost of truck $m$ to deliver in route $d$; $Z^{d,m}$ is the annual number of deliveries of truck $m$ in route $d$. $d \in D = \{0,1,2, ... r\}, m \in M = \{1,2, ... e\}$. When $d = 0$, it indicates the delivery route is undefined. Because we do not calculate the delivery cost of a supplier’s truck before entering the campuses, we assume the delivery routes of suppliers before entering the campuses are undefined.
The annual delivery cost consists of two parts: the annual delivery cost on the UP campus, and the annual delivery cost outside the UP campus. This is because the distribution center is located on the UP campus, so the deliveries from the distribution center can be more frequent. It is also because the UP campus has more than one dining halls on the campus, but each of the other campus has only one dining hall. The distribution center is connected to the warehouse in this case. Delivery cost of delivering in a route is equal to the sum of delivery costs to all the locations it covers. $DC_{d,m}^d$ can be expressed as:

$$DC_{d,m}^d = \sum_{i \in I^d, j^d} DC_i^m$$  \hspace{1cm} (3.4)

$I^d$ is the set of locations visited during the delivery in route $d$. $I^d \in I$. $I$ is the set of locations visited during the deliveries on the UP campus. $I = \{0,1,2,\ldots,15\}$. 1 to 15 indicate the dining halls, while 0 indicates the distribution center. $J^d$ is the set of locations visited during the delivery in route $d$. $J^d \in J$. $J$ indicates the locations visited during the deliveries outside the UP campus. $J = \{16,17,\ldots,26\}$. 16 to 26 indicate the dining halls, while 0 indicates the distribution center. $m \in M = \{1,2,\ldots,e\}$.

The delivery cost to a single location $DC_i^m$ can be stated as:

$$DC_i^m = TC_i^m + \sum_{k \in K} HC_i^{km}$$  \hspace{1cm} (3.5)

The transportation cost $TC_i^m$ is the sum of the truck’s fuel cost, maintenance cost and driver’s labor cost. It can be stated as:

$$TC_i^m = (tf^m + tm^m) \times ds_{[i-1],[i]} + nd^m \times dl \times tt_{[i-1],[i]}$$  \hspace{1cm} (3.6)

$i \in I^d$ for the delivery on the UP campus, and $i \in J^d$ for the delivery out of the UP campus. $[i]$ indicates the sequence of location $i$ in a route. $[i-1]$ is the previous location visited before location $i$ in sequence. In other words, $[i-1]$ indicates the start point of a traveling between two locations, and $[i]$ indicates the end point. The transportation cost varies based on different start point of the trip. $tf^m$ is the unit fuel cost in dollars per mile. The unit fuel cost per mile equals the unit gas/diesel price $pg$, in dollars per gallon, divided by the truck’s fuel consuming rate of the truck $m$: $tr^m$, in miles per gallon. So the unit fuel cost for truck $m$ is stated as:

$$tf^m = \frac{pg}{tr^m}$$  \hspace{1cm} (3.7)
The truck’s maintenance cost $tm^m$ includes the repairing cost, replacement of broken gears, and general maintenance such as changing engine oil. The drivers usually perform the maintenance after driving a certain distance, so we calculate the maintenance cost in dollars per mile. $nd^m$ is the number of drivers on the truck, which is always equal to 1. $dl$ is the driver’s unit labor cost. $tt_{[i-1],i}$ indicates the traveling time. We assume the traveling distances are the same between two locations, so the traveling times are identical too.

The handling cost $HC_{i}^{k,m}$ is the cost from both the truck drivers and workers of the school. Handling cost occurs when goods are moved in and out of a truck or a storage room. We assume there are 5 stages during a delivery process, which are shown in Table 3.2. In each stage, the handling cost $HC_{i}^{k,m}$ may include the labor cost of the workers and/or the labor cost of the truck drivers, and the equipment cost involved.

\[
HC_{i}^{k,m} = [nd^m \times dl + nw_i^k \times wl + nf_i^k \times (fc + fm)] \times t_i^k
\]

(3.8)

Forklifts are needed to help moving the goods in stage 1,2,3,4. We assume all the forklifts are the same here. $fc$ is the energy (electric) cost rate of a forklift, in dollars per hour. $fm$ is the unit maintenance cost. Because maintenance is performed after a certain period of time, the maintenance cost is calculated in dollars per hour. $t_i^k$ is the working time at each stage at location $i$. Not all the strategies involve all the stages. $t_i^k = 0$ indicates there is no stage $k$ involved in the delivery to location $i$ in a certain strategy. The stages that occur in the distribution center involve no traveling by trucks. Therefore, there are only handling cost occur at the distribution center.

3.4.3 Annual Inventory Carrying Cost (AICC)

We modify the model introduced by Ravindran et al. (2013) to build our annual inventory carrying cost model. The school uses a periodic policy to reorder the goods. The annual inventory carrying cost (AICC) model can be stated as:
\[ AICC = \sum_{i\in I} \sum_{j \in J} \sum_{h=1}^{n} \left( \frac{Q_{i,h}^f}{2} + SS_{i,h}^f \right) \times p_h^f \times cr \] (3.9)

\(Q_{i,h}^f\) is the order quantity. We assume it is equal to the demand of an order cycle, so we assume the goods in one order can be all consumed in one ordering cycle. \(SS_{i,h}^f\) is the safety stock, which is the inventory that normally should not be used. Therefore, the average inventory level is \(\frac{Q_{i,h}^f}{2} + SS_{i,h}^f\). The total inventory cost is assumed to be equal to a percent of the purchasing value of the average inventory. So the unit inventory holding cost is assumed to be equal to a percentage of the good’s value, which is \(cr\). We use the price of a product \(p_h^f\) multiplied by the average inventory level to estimate the good’s value.

### 3.4.4 LINGO model

The delivery routes from the University Park (UP) campus to the other campuses are redesigned to apply the alternative strategies. This is a typical vehicle routing problem (VRP). Each strategy contains several routes. We assume the deliveries are performed by standard full-size tractor trailer trucks, and the trucks are all identical. In each route, a truck must start from the distribution center located on the UP campus, to serve the dining halls located on 11 other campuses. Each campus only contains 1 dining hall, and the trucks deliver directly to the dining halls. Each dining hall can only be served once. No two routes are allowed to serve the same dining hall. The weight of products to be delivered in one route cannot be beyond the capacity of the trucks. The trucks must return to the distribution center at the end of a route, so the total traveling time in one route cannot be larger than the regular working time of a truck driver. For the convenience of calculation, the time limit is converted into a traveling distance limit of each route.

The VRP formulation is adapted from Filipec et al. (1998), and it is as follows:

\[
\text{Min } \sum_{i\in I} \sum_{j \in J \setminus \{i\}} \sum_{d \in D} d_{S,i,j} x_{i,j}^d
\] (3.10)

Subject to:

\[
\sum_{j \in J \setminus \{i\}} \sum_{d \in D} x_{i,j}^d = 1 \quad (\forall i \in J \setminus \{0\})
\] (3.11)
The objective function Equation 3.10 minimizes the total traveling distance in all the routes. \( x_{i,j}^d \) are binary integers. When \( x_{i,j}^d = 1 \), it indicates that a truck travels from location \( i \) to \( j \) in route \( d \); when \( x_{i,j}^d = 0 \), it indicates that a truck does not travel from location \( i \) to \( j \) in route \( d \). \( J \) indicates the set of locations visited during the deliveries. In this case \( J = \{0,16,17,...,26\} \). 0 indicates the distribution center, which is the base node. 16, 17 ..., 26 indicate the dining halls. Equation 3.11 and Equation 3.12 ensure that each location is visited exactly once. Equation 3.13 ensures the continuity of the routes; it ensures that if a truck arrives at a location it must leave that location. \( g \) indicates a location between \( i \) and \( j \). Equation 3.14 ensures that the amount of goods to be delivered in a route is not beyond the capacity of the truck. Equation 3.15 ensures that the total traveling distance of a route is not beyond the maximum allowed route length. Equation 3.16 and Equation 3.17 ensure that each route starts and ends at the distribution center. Equation 3.18 ensures that \( x_{i,j}^d \) is binary.

A LINGO model is built to solve the VRP. The LINGO model is adapted from the website of LINDO System (LINDO System, 2014). The code is shown in Appendix B. The objective of the model is to find the shortest traveling distances. It follows the constraints we introduced.

### 3.5 The Scenarios

There are four different delivery strategies; each of them has a unique delivery process, and the model is expressed differently. Therefore, we calculate the costs for the strategies separately. Each
strategy is discussed in a scenario. The strategies include the current strategy, which is currently applied delivery strategy, and three alternative strategies applying cross-docking. We want to compare the costs in the scenarios, to find the one with the lowest cost. The scenarios are presented as follows.

a) **Current Strategy**

The current strategy describes the strategy that is currently used in the delivery system; all the settings are the same as in the current situation. Different strategies are applied to vegetables and fruits, and to meats.

In the current situation, the vegetables and fruits from the suppliers (producers and wholesalers) are directly delivered to the dining halls. The suppliers pay the delivery costs. The delivery costs are charged as extra costs in the purchasing costs. The delivery process to a campus is divided into two parts: traveling outside the campus, and traveling on the campus. In this case we do not study traveling outside the campus, as we assume the school’s delivery team does not pick up from the suppliers, and the suppliers must at least deliver to the campus. We do not study the delivery to the campuses outside the UP campus, because there is only one dining hall in each of them. In the UP campus, each supplier uses its own truck to deliver to the dining halls one by one. After delivering to the last dining hall, the truck goes back to the supplier. As shown in Figure 3.1, each block indicates a stop during the delivery; the arrows show the direction of movement.
We use Equation 3.1 and Equation 3.2 to calculate the annual purchasing cost. Because the current strategy describes the costs in the current situation, it is the baseline for the other scenarios. Therefore no savings in delivery cost is applicable, $DR_h = 0$ for all the suppliers.

Because the total traveling distance on the UP campus is relatively short (about 5 miles), there is no need to design the delivery routes. The trucks usually travel from one dining hall to the nearest next dining hall, so there is only one route to serve all the dining halls, $d = 1$. This is the heuristic of a traveling salesman problem, and it is not optimal. We start calculating transportation cost when the truck enters the campus. We choose the distribution center as the start point, but there is no delivery to it. The trucks from the suppliers are full-sized tractor-trailer trucks. We use Equation 3.6 to calculate the transportation cost, where $i \in I^1 = \{1,2,...,13\}$. The delivery route starts from the distribution center and ends at the last dining hall it serves. $i = 0$ indicates the start point. $i = 1,2,...,13$ indicate the dining halls that require vegetables and fruits.

We use Equation 3.8 to calculate the handling cost. The trucks do not stop at the distribution center, so $t^k_i = 0$ when $k = 1,2,3,4$. The trucks from the suppliers unload goods at the dining halls, so there are only handling costs at the dining halls.

The delivery of vegetables and fruits to the dining halls outside the UP campus is not studied. The costs are included in the purchasing cost.
Meats are delivered in a traditional strategy. The suppliers deliver meats for all the 26 dining halls to the distribution center on the UP campus. Because the order quantities are usually big, the goods are stored in the warehouse before being redistributed to the dining halls. From the distribution center, the deliveries are done by the school’s own delivery team on the UP campus and out of the UP campus.

The process is shown in Figure 3.2:

![Diagram of delivery routes in a traditional strategy](image)

Figure 3.2: Delivery routes in a traditional strategy

In Figure 3.2, the dots indicate the items. The black dots indicate items that are assigned to a dining hall. The blocks indicate the locations. The arrows show the moving directions.

For the meats delivered on the UP campus, we use Equation 3.6 to calculate the transportation cost. Because the campus is small, only one delivery route is needed in this case, \( d = 2 \).

\[ l_i^2 = \{0, 1, 2, \ldots, 15\}, \quad i = 1, 2, \ldots, 15 \]

indicate the dining halls require meats, while \( i = 0 \) indicates the distribution center. The trucks start from the distribution center, and return to the distribution center at the end. Therefore, the delivery route’s start point and end point must be the distribution center.

The delivery process involves five stages: unloading at the distribution center, putting into the warehouse, getting out of the warehouse, loading onto the outbound trucks, and unloading at the dining halls. We use Equation 3.8 to find the handling cost in these stages. All five stages are involved.
The annual delivery cost outside the UP campus is different from the previous situation. Because the traveling distances are long, different delivery routes make the costs very different. In the current situation, the school’s delivery team designs the routes, which are shown in Table 1.1. In this case, $J^d$ is the set of locations visited in each route $d, J^d \in J = \{0, 16, 17 \ldots 26\}, d = 3, 4, \ldots 9$.

In this case, we apply Equation 3.8 to calculate the handling costs for trucks going outside the UP campus. The unloading costs at the distribution center are calculated when calculating delivery cost on the UP campus, therefore we only calculate the handling costs in the dining halls. $t^k_i = 0$ when $k = 1, 2$.

b) Post-allocate Cross-docking Strategy

The post-allocate cross-docking strategy requires no warehouse; only temporary storing is available. All goods are delivered to the distribution center by the suppliers, and redistributed by the school’s delivery team within 24 hours. The goods are sorted and assigned to the consumers after arriving at the distribution center. The process is shown in Figure 3.3:

![Figure 3.3: Item flows in a post-allocate cross-docking strategy](image)

In Figure 3.3, the dots indicate the items. The black dots indicate items that are assigned to a dining hall. The blocks indicate the locations. The arrows show the moving directions.
The delivery schedule from the distribution center depends on the schedules of the suppliers’. Meat suppliers deliver every other week, while vegetables and fruits suppliers deliver twice a week. We use Equation 3.1 and Equation 3.2 to calculate the annual purchasing cost. In this case, the wholesalers of vegetables and fruits can be cut out, because the school’s delivery team can deliver all the goods. The producers of vegetables and fruits deliver to the distribution center instead of dining halls, so the prices can be lowered. The savings of delivery cost from the producers on the UP campus can be converted into discounts for the purchasing costs. Therefore, \( DR_h > 0 \) for \( h = 1,2, \ldots, b \).

In this scenario, no central warehouse is needed. Instead, all the suppliers delivered their goods to the distribution center, and the school’s delivery team cross-dock the goods. Frozen food and fresh food can be redistributed in the same truck from the distribution center. This is applicable as some of the logistics companies deliver them together by putting the frozen food into isolation covers, and the traveling distances are relatively short. We apply Equation 3.6 to calculate the transportation cost on the UP campus. Two routes are needed here: route 1 is for delivering vegetables and fruits, and route 2 is for delivering meats. For both routes, a truck must start from the distribution center and return to it at the end. There are 15 dining halls on the UP campus; all of them need meat products, but only 13 of them need vegetables and fruits. When delivering vegetables and fruits, \( d = 1, I^1 = \{0,1,2, \ldots, 13\} \); when delivering meats, \( d = 2, I^2 = \{0,1,2, \ldots, 15\} \).

The process includes unloading at the distribution center, loading onto the outbound trucks, and unloading at the dining hall. Therefore, at the distribution center \( t_i^k = 0, k = 2,3 \).

The annual delivery cost outside the UP campus is different from the previous situation. We redesigned the delivery routes to make the deliveries more frequent. A truck can travel in any route, but only one route each day. Because the traveling distances are long, each route only covers several dining halls. Each delivery route must start from the distribution center on the UP campus and end at it too, so each delivery route is a closed loop. For the deliveries outside the UP campus, we apply Equation 3.6 to
calculate the transportation cost. \( f^d \in f = \{0, 16, 17, \ldots, 26\}. d = 3, 4, \ldots r \). The LINGO model designs the delivery routes. All the dining halls require vegetables, fruits and meats.

We apply Equation 3.8 to calculate the costs for trucks going outside the UP campus. There are only costs at the dining halls. The unloading costs at the distribution center are calculated in the previous part, therefore \( t^k = 0, k = 1, 2, 3, 4 \).

c) Pre-allocate Cross-docking Strategy

The pre-allocate cross-docking strategy is very similar to the post-allocate cross-docking strategy. The only difference is that the goods are assigned to the dining halls before arriving at the distribution center, so the total handling time at the distribution center is lowered. Because there is a request for the suppliers to assign their goods to dining halls, this may cause extra set-up cost for ordering. The item flows are shown in Figure 3.4:

![Figure 3.4: Item flows in a pre-allocate cross-docking strategy](image)

In Figure 3.4, the black dots indicate items that are assigned to a dining hall. The blocks indicate the locations. The arrows show the moving directions.
The calculation process is the same as in Scenario b).

d) Hybrid Cross-docking Strategy

In this strategy, all the suppliers deliver their goods to the distribution center, and the school’s delivery team redistributes the goods. All the vegetables and fruits are cross-docked to the dining halls on the UP campus and outside the UP campus. In this case, we assume a post-allocate cross-docking strategy is used here, as it requires less changes to the suppliers. Meats are applied the traditional strategy to be delivered. Meats and vegetables and fruits can be delivered in the same truck. There is no change to the delivery the suppliers’ schedule. Because vegetables and fruits are cross-docked, the delivery schedule from the distribution center depends on the schedules of the vegetables and fruits suppliers’. Therefore, the frequency of redistribution is twice a week. The item flows are shown in Figure 3.5:

Figure 3.5: Item flows in a hybrid cross-docking strategy

In Figure 3.5, the dots indicate meats, the triangles indicate vegetables and fruits. Items turned to black means they are assigned to a dining hall. The blocks indicate the locations. The arrows show the moving directions.
We use Equation 3.1 and Equation 3.2 to calculate the annual purchasing cost. In this case, the wholesalers of vegetables and fruits can be cut-off. The producers of vegetables and fruits deliver to the distribution center instead of dining halls, so the prices can be lowered. The savings of delivery cost from the producers on the UP campus can be converted into discounts of the purchasing costs. Therefore, 

$$DR_h > 0 \text{ for } h = 1,2, \ldots, b.$$ 

We apply Equation 3.6 to calculate the transportation cost on the UP campus. Two routes are needed: route 1 is for delivering vegetables and fruits, and route 2 is for delivering meats. For both routes, a truck must start from the distribution center and return to it at the end. There are 15 dining halls on the UP campus; all of them need meat products, but only 13 of them need vegetables and fruits. When delivering vegetables and fruits, \(d = 1, I^1 = \{0,1,2, \ldots, 13\}\); when delivering meats \(d = 2, I^2 = \{0,1,2, \ldots, 15\}\).

We apply Equation 3.8 to calculate the handling cost. For the delivery of vegetables and fruits, 

$$t^k_i = 0 \text{ when } k = 2,3. \text{ Handling costs occur when unloading the inbound trucks at the distribution center, loading the outbound trucks at the distribution center and unloading the outbound trucks at the dining halls. For the delivery of meat, } k \in K = \{1,2,3,4,5\}. \text{ Handling costs occur at all the five stages.}$$

For the deliveries outside the UP campus, we apply Equation 3.6 to calculate the transportation cost. \(J^d \in J = \{0,16,17, \ldots, 26\}, d = 3,4, \ldots r\). The LINGO model designs the delivery routes. All the dining halls require vegetables, fruits and meats. The school’s trucks deliver all the products.

In this case, we apply Equation 3.8 to calculate the handling costs for trucks going outside the UP campus. The unloading costs at the distribution center are calculated in the previous part. For meats handling costs occur when getting items out of the warehouse, loading the outbound trucks at the distribution center and unloading the outbound trucks at the dining halls. So \(t^k_i = 0 \text{ when } k = 1,2 \text{ in this case.}$$ For vegetables and fruits, \(t^k_i = 0 \text{ when } k = 1,2,3. \text{ Handling costs occur when loading the outbound trucks in the distribution center, and unloading the outbound trucks at the dining halls.}$$
Chapter 4

Empirical Study and Results

4.1 Empirical Study

An empirical study based on the case of the food delivery system of Penn State University is presented in this section. The main aim is to compare four possible delivery strategies to find the strategy with the lowest total cost, using the cost comparison model we introduced in the previous chapter.

Based on the private policy of the school, we cannot be provided any prices of the items. Instead, the prices are from the website of U.S. Department of Agriculture (USDA), which are shown in Appendix D. To purchase from the producers instead of the wholesalers, the price for the same item can be reduced by 20% to 40%. In this research, a worst case is considered, so the discount is assumed to be 20% for all the items. Currently, only the order quantity of vegetables and fruits for the University Park (UP) campus is big enough to purchase from the producers. The average salary of a worker in the dining halls and the distribution center is $13.8/hour (Penn State University Human Resource Office, 2013). There is one driver in each truck (inbound and outbound). The average salary of a truck driver is $18.62/hour (salary.com, 2013). There are five main stages during the delivery process. The stages and the resources involved at each stage are listed below:

<table>
<thead>
<tr>
<th>Stage</th>
<th>Explanation</th>
<th>Number of workers</th>
<th>Number of forklifts</th>
<th>Average working time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unload inbound truck at distribution center</td>
<td>3</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>Put items into warehouse</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>Get items out of warehouse</td>
<td>2</td>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>4</td>
<td>Load outbound truck at distribution center</td>
<td>2</td>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>5</td>
<td>Unload inbound truck at dining hall (inside UP campus)</td>
<td>1</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>5</td>
<td>Unload inbound truck at dining hall (outside UP campus)</td>
<td>2</td>
<td>1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 4.1: Resources needed at each stage
The inventory carrying cost rate is 15% of the item’s value. In the alternative strategies, the delivery frequencies from the suppliers are the same as in the current situation. Meats and fresh produces are redistributed together from the distribution center. This is possible as some of the logistics companies deliver them together by putting the frozen food into isolation covers. This strategy is applicable here as the traveling distances are relatively short. The delivery information is shown in Table 4.2:

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Supplier Type</th>
<th>Item Type</th>
<th>Delivery Day</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplier 1</td>
<td>Producer</td>
<td>Vegetables and Fruits</td>
<td>Tuesday, Friday</td>
<td>Twice a week</td>
</tr>
<tr>
<td>Supplier 2</td>
<td>Producer</td>
<td>Vegetables and Fruits</td>
<td>Tuesday, Friday</td>
<td>Twice a week</td>
</tr>
<tr>
<td>Supplier 3</td>
<td>Producer</td>
<td>Vegetables and Fruits</td>
<td>Tuesday, Friday</td>
<td>Twice a week</td>
</tr>
<tr>
<td>Supplier 4</td>
<td>Producer</td>
<td>Vegetables and Fruits</td>
<td>Tuesday, Friday</td>
<td>Twice a week</td>
</tr>
<tr>
<td>Supplier 5</td>
<td>Producer</td>
<td>Vegetables and Fruits</td>
<td>Tuesday, Friday</td>
<td>Twice a week</td>
</tr>
<tr>
<td>Supplier 6</td>
<td>Producer</td>
<td>Meat</td>
<td>Friday</td>
<td>Once every other week</td>
</tr>
<tr>
<td>Supplier 7</td>
<td>Producer</td>
<td>Meat</td>
<td>Tuesday</td>
<td>Once every other week</td>
</tr>
<tr>
<td>Supplier 8</td>
<td>Producer</td>
<td>Meat</td>
<td>Monday</td>
<td>Once every other week</td>
</tr>
<tr>
<td>Supplier 9</td>
<td>Producer</td>
<td>Meat</td>
<td>Tuesday</td>
<td>Once every other week</td>
</tr>
<tr>
<td>Supplier 10</td>
<td>Producer</td>
<td>Meat</td>
<td>Thursday</td>
<td>Once every other week</td>
</tr>
</tbody>
</table>

Table 4.2: The suppliers and their delivery frequencies

The dining halls are open all year long except 7 weeks: the Spring break (1 week), end of Spring semester (1 week), end of Summer semester (1 week), Thanksgiving break (1 week), Christmas & New Year’s break (3 weeks). Therefore, we assume the dining halls are open 45 weeks in a year.

The trucks used to deliver between campuses are standard full-size tractor-trailer trucks, whose average diesel consumption is 10 miles/gallon (U.S. Department of Energy, 2005). The maintenance and depreciation cost of the trucks is about $0.1/mile (Truckers Report, 2013). The average price of diesel in Pennsylvania is $3.89/gallon, by 11/1/2013. The trucks used to deliver on the UP campus are Ford LCF box trucks, whose average gas consumption is 18 miles/gallon. The maintenance and depreciation cost of the trucks is about $0.07/mile (Ford, 2013). The average price of regular gasoline in Pennsylvania is $3.55/gallon, by 11/1/2013. The forklifts used in the distribution center and dining halls are produced by Caterpillar. The operational cost (fuel cost) is about $1.28/hour, and the maintenance cost is about $1/hour (Caterpillar, 2013).
As introduced in Chapter 2.6, the weight capacity of a standard full-sized tractor-trailer truck is 34,000 lbs. The volume capacity is 3059 ft\(^3\). The maximum payload of a LCF box truck is 6,000 lbs. The volume is about 1,275 ft\(^3\) (Ford, 2013). According to Ravindran et al. (2013), a “full” truck means 80% of the original volume is occupied; so the maximum volume is 1020 ft\(^3\). One standard case of the item is 40 lbs with a volume of 0.875 ft\(^3\). Therefore, when the total weight of the items reaches the truck’s weight limit, the volume is 743.75 ft\(^3\), which is much less than the maximum volume. As a result, we do not consider volume as a constraint in the VRP model.

The traveling distances and traveling times on the UP campus for vegetables and fruits are shown in Table 4.3. The traveling distances and traveling times on the UP campus for meats are shown in Table 4.4. These routes are unchanged in all the scenarios. In both of the two tables, the first row indicates the categories of the data. The first column indicates the relative positions, which means the order of them to be served. The second column indicates the locations’ names. The third column indicates the traveling distances from the previous location to current location, and the fourth column indicates the traveling times between the two locations.

<table>
<thead>
<tr>
<th>([i])</th>
<th>Location’s Name</th>
<th>(d_{s[i-1][i]}) (Mile)</th>
<th>(t_{t[i-1][i]}) (Hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Central Distribution Center</td>
<td>(\backslash)</td>
<td>(\backslash)</td>
</tr>
<tr>
<td>1</td>
<td>Blue Chip Bistro</td>
<td>0.4</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>Warnock Commons</td>
<td>0.1</td>
<td>0.017</td>
</tr>
<tr>
<td>3</td>
<td>Schultz Child Care</td>
<td>0.2</td>
<td>0.017</td>
</tr>
<tr>
<td>4</td>
<td>Café Laura</td>
<td>0.3</td>
<td>0.05</td>
</tr>
<tr>
<td>5</td>
<td>Waring Commons</td>
<td>0.7</td>
<td>0.067</td>
</tr>
<tr>
<td>6</td>
<td>HUB</td>
<td>1.3</td>
<td>0.1</td>
</tr>
<tr>
<td>7</td>
<td>Redifer Commons</td>
<td>0.3</td>
<td>0.033</td>
</tr>
<tr>
<td>8</td>
<td>Bennett Family Center</td>
<td>0.2</td>
<td>0.017</td>
</tr>
<tr>
<td>9</td>
<td>Pollock Hall</td>
<td>0.3</td>
<td>0.033</td>
</tr>
<tr>
<td>10</td>
<td>Campus Catering</td>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>11</td>
<td>Findley Commons</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>BJC</td>
<td>0.8</td>
<td>0.068</td>
</tr>
<tr>
<td>13</td>
<td>Mount Nittany Club</td>
<td>0.1</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Table 4.3: Traveling distances and traveling times on the UP campus for vegetables and fruits
<table>
<thead>
<tr>
<th>$i$</th>
<th>Location’s Name</th>
<th>$ds_{[i-1],[i]}$ (Mile)</th>
<th>$tt_{[i-1],[i]}$ (Hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Central Distribution Center</td>
<td>\</td>
<td>\</td>
</tr>
<tr>
<td>1</td>
<td>Blue Chip Bistro</td>
<td>0.4</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>Warnock Commons</td>
<td>0.1</td>
<td>0.017</td>
</tr>
<tr>
<td>3</td>
<td>Schultz Child Care</td>
<td>0.2</td>
<td>0.017</td>
</tr>
<tr>
<td>4</td>
<td>Café Laura</td>
<td>0.3</td>
<td>0.05</td>
</tr>
<tr>
<td>5</td>
<td>Nittany Lion Inn</td>
<td>0.5</td>
<td>0.033</td>
</tr>
<tr>
<td>6</td>
<td>Waring Commons</td>
<td>0.4</td>
<td>0.05</td>
</tr>
<tr>
<td>7</td>
<td>HUB</td>
<td>1.3</td>
<td>0.1</td>
</tr>
<tr>
<td>8</td>
<td>Redifer Commons</td>
<td>0.3</td>
<td>0.033</td>
</tr>
<tr>
<td>9</td>
<td>Bennett Family Center</td>
<td>0.2</td>
<td>0.017</td>
</tr>
<tr>
<td>10</td>
<td>Pollock Hall</td>
<td>0.3</td>
<td>0.033</td>
</tr>
<tr>
<td>11</td>
<td>Campus Catering</td>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>12</td>
<td>Findley Commons</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>BJC</td>
<td>0.8</td>
<td>0.068</td>
</tr>
<tr>
<td>14</td>
<td>Mount Nittany Club</td>
<td>0.1</td>
<td>0.017</td>
</tr>
<tr>
<td>15</td>
<td>Penn Stater Hotel</td>
<td>1.9</td>
<td>0.083</td>
</tr>
</tbody>
</table>

Table 4.4: Traveling distances and traveling times on the UP campus for meats

The current delivery routes outside the UP campus are shown in Figure 4.1:

![Figure 4.1: Current truck delivery routes](image)

In Figure 4.1, the arrows show the delivery directions, not the actual traveling paths. Different colors indicate different routes. The dots indicate the campuses. The delivery schedule is the same as the
current delivery schedule, as shown in Table 1.1. One tractor-trailer truck is needed to deliver the goods.

Table 4.5 shows the distances between two campuses. The first column shows the names of the start points, and the first row shows the names of the end points.

<table>
<thead>
<tr>
<th>i</th>
<th>j</th>
<th>0</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
<th>26</th>
</tr>
</thead>
<tbody>
<tr>
<td>University Park</td>
<td>0</td>
<td>-</td>
<td>41.2</td>
<td>167</td>
<td>211</td>
<td>142</td>
<td>133</td>
<td>99.9</td>
<td>114</td>
<td>99.7</td>
<td>121</td>
<td>123</td>
<td>151</td>
</tr>
<tr>
<td>Altoona</td>
<td>16</td>
<td>41.2</td>
<td>-</td>
<td>132</td>
<td>204</td>
<td>195</td>
<td>95.6</td>
<td>146</td>
<td>154</td>
<td>100</td>
<td>162</td>
<td>162</td>
<td>191</td>
</tr>
<tr>
<td>Beaver</td>
<td>17</td>
<td>167</td>
<td>132</td>
<td>-</td>
<td>119</td>
<td>293</td>
<td>47.9</td>
<td>243</td>
<td>298</td>
<td>204</td>
<td>286</td>
<td>288</td>
<td>318</td>
</tr>
<tr>
<td>Behrend</td>
<td>18</td>
<td>211</td>
<td>204</td>
<td>119</td>
<td>-</td>
<td>356</td>
<td>148</td>
<td>314</td>
<td>282</td>
<td>295</td>
<td>322</td>
<td>280</td>
<td>316</td>
</tr>
<tr>
<td>Berks</td>
<td>19</td>
<td>142</td>
<td>195</td>
<td>293</td>
<td>356</td>
<td>-</td>
<td>245</td>
<td>56.1</td>
<td>54.5</td>
<td>116</td>
<td>30.7</td>
<td>91.3</td>
<td>97.5</td>
</tr>
<tr>
<td>Great Allegheny</td>
<td>20</td>
<td>133</td>
<td>95.6</td>
<td>47.9</td>
<td>148</td>
<td>245</td>
<td>-</td>
<td>195</td>
<td>245</td>
<td>157</td>
<td>239</td>
<td>252</td>
<td>282</td>
</tr>
<tr>
<td>Harrisburg</td>
<td>21</td>
<td>99.9</td>
<td>146</td>
<td>243</td>
<td>314</td>
<td>56.1</td>
<td>195</td>
<td>-</td>
<td>88.2</td>
<td>69.3</td>
<td>59.1</td>
<td>124</td>
<td>131</td>
</tr>
<tr>
<td>Hazleton</td>
<td>22</td>
<td>114</td>
<td>154</td>
<td>298</td>
<td>282</td>
<td>54.5</td>
<td>245</td>
<td>88.2</td>
<td>-</td>
<td>137</td>
<td>34.4</td>
<td>37.4</td>
<td>43.6</td>
</tr>
<tr>
<td>Mont Alto</td>
<td>23</td>
<td>99.7</td>
<td>100</td>
<td>204</td>
<td>295</td>
<td>116</td>
<td>157</td>
<td>69.3</td>
<td>137</td>
<td>-</td>
<td>107</td>
<td>168</td>
<td>179</td>
</tr>
<tr>
<td>Schuylkill</td>
<td>24</td>
<td>121</td>
<td>162</td>
<td>286</td>
<td>322</td>
<td>30.7</td>
<td>239</td>
<td>59.1</td>
<td>34.4</td>
<td>107</td>
<td>-</td>
<td>70.4</td>
<td>77.4</td>
</tr>
<tr>
<td>Wikes-Barre</td>
<td>25</td>
<td>123</td>
<td>162</td>
<td>288</td>
<td>280</td>
<td>91.3</td>
<td>252</td>
<td>124</td>
<td>37.4</td>
<td>168</td>
<td>70.4</td>
<td>-</td>
<td>31.2</td>
</tr>
<tr>
<td>Worthington Scranton</td>
<td>26</td>
<td>151</td>
<td>191</td>
<td>318</td>
<td>316</td>
<td>97.5</td>
<td>282</td>
<td>131</td>
<td>43.6</td>
<td>179</td>
<td>77.4</td>
<td>31.2</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.5: Traveling distances between campuses (in miles)

### 4.2 Result and Analysis

First, we find the optimized delivery routes outside the UP campus. The routes in Scenario a) are the same as in the current situation. In the other scenarios, we want to find the routes with the shortest total traveling distance.

The routes in Scenario b) and c) are designed by LINGO. The routes are:

Route 1: University Park > Behrend > University Park

Route 2: University Park > Berks > Harrisburg > Mont Alto > University Park

Route 3: University Park > Wikes-Barre > Worthington Scranton > Hazleton > Schuylkill > University Park

Route 4: University Park > Greater Allegheny > Beaver > Altoona > University Park
Four tractor-trailer trucks are needed to serve all the four routes, as a pure cross-docking strategy requires the goods to be delivered when they arrive at the distribution center. The routes are shown on the map in Figure 4.2. The arrows show the delivery directions, not the actual traveling paths. Different colors indicate different routes. The dots indicate the campuses. As we can see from Table 4.2, there are four days in a week when suppliers can come. Because meats are delivered from the suppliers once every other week, while vegetables and fruits are delivered twice a week, the average weekly delivery frequency is 3 times.

![Figure 4.2: Truck delivery routes via pure cross-docking](image)

Then we find the optimized routes in Scenario d). In a hybrid cross-docking strategy, meats from the suppliers are stored in the warehouse on the UP campus; vegetables and fruits are cross-docked immediately at the distribution center on the UP campus. The deliveries outside the UP campus are made twice a week, for meats, vegetables and fruits. The amount of meats in each delivery is for a three-day demand. Because some dining halls have too small demands and are too far away from the distribution center, the savings from applying a bulk buying strategy cannot cover the extra delivery cost by applying cross-docking to them. By comparing the delivery costs and the possible discount savings, we decide not to apply cross-docking to the dining halls on the Beaver campus, the Greater Allegheny campus, the Schuylkill campus, the Wilkes-Barre campus and the Worthington Scranton campus. Therefore, only
meats are delivered to them, but vegetables and fruits are still purchased from their local wholesalers. The routes designed by LINGO are:

Route 1: University Park > Altoona > Behrend > University Park
Route 2: University Park > Mont Alto > Harrisburg > Berks > Hazleton > University Park
Route 3: University Park > Greater Allegheny > Beaver > University Park
Route 4: University Park > Wilkes-Barre > Worthington Scranton > Schuylkill > University Park

The first two routes cover dining halls that we apply cross-docking strategy to. Two tractor-trailer trucks are needed to deliver twice a week, at Tuesday and Friday, which are the days when vegetables and fruits are delivered from the suppliers. The other two routes cover dining halls that we do not apply cross-docking strategy to. One truck is needed to deliver once every two weeks, at Monday or Wednesday or Thursday. Therefore, 2 trucks are needed in total.

The delivery routes designed by the LINGO model are shown in Figure 4.3. The arrows show the delivery directions between locations, not the actual traveling paths. Different colors indicate different routes. The dots indicate the campuses

![Image](image.png)

Figure 4.3: Truck delivery routes via Hybrid cross-docking

Under the hybrid cross-docking strategy, because we do not apply cross-docking to all the campuses, we do not buy vegetables and fruits for all the campuses. However, currently the order quantity for the UP campus is big enough to apply a bulk buying strategy; so we know that even though we can
only consolidate orders from some of the campuses, as long as the UP campus is included, we always have a big enough order quantity to apply a bulk buying strategy.

After designing the routes, we can calculate the costs.

Suppliers in the current strategy perform the delivery of vegetables and fruits on the UP campus; it costs about $104,000 a year for the suppliers, and this is a part of the purchasing cost to the school. If the school’s delivery team performs the deliveries, this cost can be eliminated, which means a 2.8% discount in the purchasing cost. The APCs under different strategies to the school are shown in Table 4.6. The first column indicates the name of the strategy being used. The first row indicates the category of goods being delivered. The numbers indicate the annual purchasing costs of the strategies, for different kinds of good.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>APC for vegetables and fruits</th>
<th>APC for meats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current strategy</td>
<td>$3,704,000</td>
<td>$5,445,000</td>
</tr>
<tr>
<td>Pre-allocate cross-docking</td>
<td>$3,513,600</td>
<td>$5,445,000</td>
</tr>
<tr>
<td>Post-allocate cross-docking</td>
<td>$3,513,600</td>
<td>$5,445,000</td>
</tr>
<tr>
<td>Hybrid cross-docking</td>
<td>$3,528,000</td>
<td>$5,445,000</td>
</tr>
</tbody>
</table>

Table 4.6: The annual purchasing costs after optimizing routes for different strategies

The school's delivery team does the other deliveries. The ADCs for the school are shown in Table 4.7. The first column indicates the names of the scenarios. The first row indicates where the delivery costs occur. The numbers indicate the annual delivery costs of different strategies, in different places.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>ADC of Dining halls on the UP campus</th>
<th>ADC of Dining halls outside the UP campus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current strategy</td>
<td>$58,100</td>
<td>$125,030</td>
</tr>
<tr>
<td>Pre-allocate cross-docking</td>
<td>$89,280</td>
<td>$338,790</td>
</tr>
<tr>
<td>Post-allocate cross-docking</td>
<td>$89,280</td>
<td>$338,790</td>
</tr>
<tr>
<td>Hybrid cross-docking</td>
<td>$89,280</td>
<td>$219,750</td>
</tr>
</tbody>
</table>

Table 4.7: The annual delivery costs for different strategies

The AICCs are shown in Table 4.7. The first column indicates the name of the strategy being used. The first row indicates the category of goods being delivered. The numbers indicate the annual delivery costs of the strategies, for different items.
<table>
<thead>
<tr>
<th></th>
<th>AICC for vegetables and fruits</th>
<th>AICC for meats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current strategy</td>
<td>$6,000</td>
<td>$36,300</td>
</tr>
<tr>
<td>Pre-allocate cross-docking</td>
<td>$5,880</td>
<td>$36,300</td>
</tr>
<tr>
<td>Post-allocate cross-docking</td>
<td>$5,880</td>
<td>$36,300</td>
</tr>
<tr>
<td>Hybrid cross-docking</td>
<td>$5,880</td>
<td>$36,300</td>
</tr>
</tbody>
</table>

Table 4.8: The annual inventory costs for different strategies

By adding the costs up, we have the annual total cost (ATC), as shown in Table 4.9. The first column indicates the name of the strategy being used. The numbers indicate the ATCs of the strategies.

<table>
<thead>
<tr>
<th></th>
<th>ATC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current strategy</td>
<td>$9,374,430</td>
</tr>
<tr>
<td>Pre-allocate cross-docking</td>
<td>$9,428,850</td>
</tr>
<tr>
<td>Post-allocate cross-docking</td>
<td>$9,428,850</td>
</tr>
<tr>
<td>Hybrid cross-docking</td>
<td>$9,324,210</td>
</tr>
</tbody>
</table>

Table 4.9: The annual total cost for different strategies

As a result, the hybrid cross-docking strategy has the lowest ATC; it can save about $50,000 a year from the current strategy. For the suppliers of vegetables and fruits, we no longer need them to deliver to the dining halls, and we can convert the savings into a 2.8% purchasing discount from them.
Chapter 5

Conclusion and Future Work

5.1 Conclusion

This research introduces a new method to reduce costs in the food delivery system in Penn State University. As the result of the research shows, the best strategy to be applied in this case is the hybrid cross-docking strategy, which has the lowest total cost among all the alternative strategies. This strategy has the benefits as in a cross-docking strategy, so that it enables lower handling cost and inventory carrying cost than those in a traditional delivery strategy. It also has the benefits as in a traditional delivery strategy, so it enables the school to keep some inventories to lower the risk of backorder. Compared to the current strategy, to the dining halls and stores on the University Park campus, by applying cross-docking the school’s own delivery team can deliver the vegetables and fruits on the campus, which saves delivery costs from delivery by vendors. It also solves the “last-mile logistics” problem of the vendors, as they do not need to struggle in the delivery across the campus. As the school’s delivery team uses much smaller trucks than those used by the vendors, the transportation on the campus can be much easier to perform. To the dining halls on the campuses outside the University Park campus, it enables the central distribution center to deliver more frequently. What’s more, this strategy enables the school to apply a bulk buying strategy to vegetables and fruits, to reduce purchasing costs. Even though some of the dining halls cannot be applied cross-docking strategy to, the costs on these campuses remain the same as before, so no extra costs occur. In total, the new strategy reduces the total cost of food purchasing and delivery system in Penn State University, with a faster distribution process.
5.2 Future Work

Recently, more and more people start to notice the importance of “last-mile logistics”. To the food industry, keeping the delivery time short is very important, as the lifetimes of foods are usually not long. Therefore, the carriers of food products are eager to find a way to reduce the delivery time. This study provides them a possible approach to this goal, by applying a cross-docking strategy. As we have shown in the research, a cross-docking strategy can reduce the costs to a food delivery system. This strategy cannot only be used to a university, but also to other places with huge demands and crowded traffic conditions, such as office buildings, hospitals and shopping malls in the cities. A distribution center can be built near these locations, to consolidate goods from different suppliers. Furthermore, a cross-docking strategy can be applied to other items that have short life times, such as medicines and some seasonal products.

Beside the benefits we have discussed, there are more potential benefits from applying cross-docking. For example, because smaller trucks are used to perform the “last-mile” deliveries, the traffic condition will be better in the urban areas. On the other hand, as cross-docking is a relatively new technique, there is still more research work to be done to overcome its drawbacks. Applying cross-docking requires a well organized system to coordinate different departments, and the ability to deal with a large amount of orders in a short time. Because of these restrictions, it is difficult for cross-docking to be widely used.

Hybrid cross-docking is one of the alternatives that modified from a pure cross-docking strategy. There are still new possible strategies, which can reduce the costs more. In the future, we may find alternative ways to apply to the food delivery system, and reduce even more costs than the current strategy.
Bibliography


Appendix A: Introduction to the campuses served by the central warehouse and distribution center

1) **Penn State Erie-Behrend College**: it has 1 dining hall and 5 cafes, located in 3 different buildings. Its Dobbins Dining hall serves all-you-can-eat buffet for breakfast, lunch and dinner, while the cafes serves only fast food and beverages. The distance between the Behrend College and the University Park campus is 207 miles, which is the farthest campus from the University Park campus. However, it is a very large campus with over 4,300 students in total, and about 1,750 live on campus, which means a big demand of the dining hall. As a result, the central distribution center still needs to deliver 3 times in two weeks.

2) **Penn State Altoona**: the nearest campus to University Park, only 40 miles away. There are 4 cafes prepare food to about 1,700 students eating every day. As the campus is near, the items are delivered to it twice a week. However, the central distribution center does not supply vegetables or fruits to it.

3) **Penn State Harrisburg**: only about 100 miles from the University Park campus. However, the number of students living on campus is small, only about 427. As there are few students eating in the dining hall, only 2 dining areas in this campus. The items are delivered once a week.

4) **Penn State Mont Alto**: 110 miles from University Park. It is also a small campus, with only 1,200 students, served by one dining hall. The products are delivered once a week to this campus, at the same time with Altoona and Harrisburg.

5) **Penn State Wikes-Barre**: about 118 miles away from University Park. It is the smallest campus with only 680 students in total. There is no on-campus housing available to the students, but there are two cafes for the students to dine in.
6) **Penn State Worthington Scranton**: close to Penn State Wikes-Barre campus, with 1,400 students, with one dining hall to serve them. As the two campuses are both small, they are served together once every two weeks.

7) **Penn State Hazleton**: about 114 miles away from University Park. There is one residence hall and two cafes, serving about 450 students live on campus.

8) **Penn State Schuylkill**: about 120 miles away from University Park. There are about 350 students living on campus, with only one residence hall and one dining hall.

9) **Penn State Berks**: 800 students live on campus. Hazleton, Schuylkill and Berks campus are very close to each other, about 30 miles from each other; also because they do not have a big demand with fewer students, they are always served together once a week.

10) **Penn State Greater Allegheny**: on the west side of the state, about 108 miles from University Park. There is only one dining hall, serving about 200 students each day.

11) **Penn State Beaver**: about 50 miles from Greater Allegheny. There are about 200 students served by one dining hall. As Greater Allegheny and Beaver are not big and located close to each other, the two dining halls are served together once every other week.
Appendix B: LINGO Code

Delivery via Pure Cross-docking Strategy

MODEL:

SETS:
! Definitions:
Parameters:
  Q(i) is the amount required at city i,
  DIST(i,j) is the distance from city i to city j,
Variables:
  X(i,j) = 1 if some vehicle travels from city i to city j, else 0,
  U(i) is the accumulated deliveries at city i ;
! Time related definitions:
Parameters:
  TMPM = time per mile,
  TME(k) = earliest allowed arrival time at stop k,
  TML(k) = latest allowed arrival time at k,
  TMV(k) = stop or visit time at k,
  TMAX = maximum time for any trip
  MXTRK = maximum number of trucks
Variables:
  TMA(k) = arrival time at K;
CITY: Q, U, TD, TME, TML, TMV, TMA;
CXC( CITY, CITY): DIST, X;
ENDSETS

DATA:
  TMPM = 1.2;
  TMAX = 99999;
! location 0 represents the common depot;
!  0 16 17 18 19 20 21 22 23 24 25 26;
CITY = UP Alt Brd Berk Hbg Haz MA Sch WB WS Beav GA;
! Amount to be delivered to each customer;
  Q = 0 10 15 6 5 5 4 5 6 2 4 3;
! Earliest time;
  TME= 0 1000 2800 2000 1800 3600 3500 2400 100 1500 1800 1900;
! Latest time;
  TML=99999 2500 2900 3000 3900 3900 3900 3800 800 2400 2800 3800;
! Unloading time
  TMV = 0 30 30 30 30 30 30 30 30 30 30 30;
DIST =
! UP Alta Brd Berk Hbg Haz MA Sch WB WS Beaver GA From;
  0 41.2 211 142 99.9 114 110 121 118 151 167 108 !DC;
  41.2 0 196 181 146 154 100 162 162 191 132 96 !Alta;
  211 196 0 356 314 282 295 322 280 316 119 148 !Brd;
  142 181 356 0 56.1 54.5 116 30.7 91.3 97.5 293 245 !Berk;
  99.9 146 314 56.1 0 88.2 69.3 59.1 124 131 243 195 !Hbg;
  114 154 282 54.5 88.2 0 137 34.4 37.4 43.6 298 245 !Haz;
  110 100 295 116 69.3 137 0 107 168 179 204 157 !MA;
  121 162 322 30.7 59.1 34.4 107 0 70.4 77.4 286 239 !Sch;
VCAP = 30;  ! Capacity of a truck;
DMAX = 450;  ! Max distance allowed in one route;
MXTRK = 9999;  ! Max number of vehicles allowed;
ENDDATA

SUBMODEL VROUTE:

! Minimize total travel distance;
MIN = TDIST;
TDIST = @SUM( CXC: DIST * X);

@FOR( CITY(k):)
! a vehicle does not travel inside itself,...;
X( k, k) = 0;
);

! For each city, except depot....;
@FOR( CITY( k)| k #GT# 1:)
! a vehicle must enter city K from some city I,...;
[NTR] @SUM( CITY( i)| i #NE# k #AND# ( i #EQ# 1 #OR#
Q( i) + Q( k) #LE# VCAP): X( i, k)) = 1;

! a vehicle must leave K after service to some city J;
[XIT] @SUM( CITY( j)| j #NE# k #AND# ( j #EQ# 1 #OR#
Q( j) + Q( k) #LE# VCAP): X( k, j)) = 1;

! U( k) is at least amount needed at K, but can't exceed vehicle capacity;
@BND( Q( k), U( k), VCAP);

! If K follows I, then can bound U( k) - U( i);
@FOR( CITY( i)| i #NE# k #AND# i #NE# 1:
[UL] U( k) >= U( I) + Q( k) - VCAP + VCAP * 
( X( k, i) + X( i, k)) - ( Q( k) + Q( i))
* X( k, i);
);

! If K is 1st stop, then U( k) = Q( k);
U( k) <= VCAP - ( VCAP - Q( k)) * X( 1, k);

! If K is not 1st stop...;
U( k)>= Q( k) + @SUM( CITY( i)|
I #GT# 1: Q( i) * X( i, k));
);

! Compute the total distance traveled by the vehicle through J;
@FOR( CITY( j):)
[R_TD_1] TD( j) >= DIST( 1, j)* X( 1, j);
@FOR( CITY( i)| i #GT# 1:
[R_TD] TD( j) >= TD( i) + DIST( i, j)*X(i,j) - DMAX * ( 1 - X(i, j))
! Longest trip cannot exceed max trip length;
TD(1) <= DMAX;

! Make the X's binary;
@FOR( CXC: @BIN( X));

! TMPM = time per mile,
TME(k) = earliest allowed arrival time at stop K,
TML(k) = latest allowed arrival time at K,
TMV(k) = stop or visit time at K,
TMAX = maximum time for any trip, e.g., 11 hrs in US,

! Time window related constraints;
@FOR( CITY(k)| k #GT# 1:
  @FOR( CITY(i) | i #NE# k:
    ! Time of arrival at K if preceding stop was I;
    [RTM] TMA(k) >= TMA(i) + ( TMV(i) + TMPM*DIST(i,k))*(X(i,k)
    -TML(i)*(1-X(i,k));
    ! Must arrive within the [TME, TML] window. We are allowed to wait
    in order to arrive no earlier than TME(k);
    @BND( TME(k), TMA(k), TML(k));
  );
)

! Max trip time constraint, assumes distance matrix
satisfies triangle inequality;
[XT] TMA(k) + TMV(k) + TMPM*DIST(k,1)*X(k,1) <= TMAX;
)

! Minimum no. vehicles required, fractional
and rounded up;
VEHCLF = @SUM( CITY(I)| I #GT# 1: Q(I))/ VCAP;
VEHCLR = VEHCLF + 1.999 -
@WRAP( VEHCLF - .001, 1);
! Must send enough vehicles out of depot;
@SUM(CITY(j) | j #GT# 1: X(1,j)) >= VEHCLR;

! Max vehicles\trucks constraint;
@SUM(CITY(j) | j #GT# 1: X(1,j)) <= MXTRK;
ENDSUBMODEL

CALC:
@SET( 'TERSEO', 1); ! Make output somewhat terse;
@SET('IPTOLR', .01); ! Relative optimality tolerance;
@SET('TIM2RL', 30); ! Time to turn on IPTOLR in seconds;

@SOLVE( VROUTE);

ISTAT = @STATUS();

@IFC( ISTAT #EQ# 0 #OR# ISTAT #EQ# 4: ! Do report only if optimal or feas-
      sible;
      FW = 12;
      NROUTES = 0;
WRITE( @NEWLINE(2), 'Vehicle Routing Trip Report', @NEWLINE(1),
'       Total distance= ', TDIST);
! Write a listing of the routes;
FOR( CITY( j):
IF( X( 1, j) #GT# .5:  ! City j first on trip? ;
NROUTES = NROUTES + 1;
WRITE( @NEWLINE( 2), 'ROUTE ', NROUTES, ':', @NEWLINE( 1));
WRITE( FROM TO ARR TIME', @NEWLINE( 1));
WRITE(----------------------------------------', @NEWLINE( 1));
WRITE( ', CITY( 1), (FW-@STRLEN( CITY( 1)))*',
CITY( j), (FW-@STRLEN( CITY( j)))*',
@FORMAT( TMA( j), '10.1f'), @NEWLINE( 1)));
IPOS = J;
WHILE( IPOS #NE# 1:
NLOOPS = NLOOPS + 1;
FOR( CITY( J2):  ! Which city J2 follows city IPOS? ;
IF( X( IPOS, J2) #GT# .5:
IF( J2 #NE# 1:  ! Have we returned to depot? ;
WRITE( ', CITY( IPOS), (FW-@STRLEN( CITY( IPOS)))*',
CITY( J2), (FW-@STRLEN( CITY( J2)))*',
@FORMAT( TMA( J2), '10.1f'), @NEWLINE( 1)));
ELSE
WRITE( ', CITY( IPOS), (FW-@STRLEN( CITY( IPOS)))*',
CITY( 1), (FW-@STRLEN( CITY( 1)))*',
@FORMAT( TMA( IPOS) + TMV( IPOS) + TMPM * DIST( IPOS, 1),
'10.1f'), @NEWLINE( 1)));
IPOS = J2;
BREAK;
);)
);)
);)
);)
);)
);)
);)
ENDCALC
Delivery via Hybrid Cross-docking Strategy

! The Vehicle Routing Problem (VRP), with time windows (VRouteWindow);
! Keywords: Vehicle Routing, Routing, LTL Delivery, Time Windows;

SETS:
! Definitions:
Parameters:
  Q(i) is the amount required at city i,
  DIST(i,j) is the distance from city i to city j,
Variables:
  X(i,j) = 1 if some vehicle travels from city i to city j, else 0,
  U(i) is the accumulated deliveries at city i ;

! Time related definitions:
Parameters:
  TMPM = time per mile,
  TME(k) = earliest allowed arrival time at stop k,
  TML(k) = latest allowed arrival time at k,
  TMV(k) = stop or visit time at k,
  TMAX = maximum time for any trip
  MXTRK = maximum number of trucks\vehicles.
Variables:
  TMA(k) = arrival time at K;
CITY: Q, U, TD, TME, TML, TMV, TMA;
CXC( CITY, CITY): DIST, X;

ENDSETS

DATA:
  TMPM = 1.2;
  TMAX = 99999;

! location 0 represents the common depot;
! 0 1 2 3 4 5 6 ;
CITY = UP  Alt Brd Berk Hbg Haz MA ;
! Amount to be delivered to each customer;
  Q =  0  10  15  6  5  5  4 ;
! Earliest time;
  TME= 0 1000 2800 2000 1800 3600 3500 ;
! Latest time;
  TML=99999 2500 2900 3000 3900 3900 3900 ;

  TMV = 0 30 30 30 30 30 30 ;
! city 1 represents the common depot, i.e. Q( 1) = 0;
! city 1 represents the common depot, i.e. Q( 1) = 0;
! Distance from city I to city J is same(but need not be) from J to I,
distance from city I to the depot maybe 0(but need not be),
if vehicle need not return to the depot ;

DIST =
! UP  Alta Brd Berk Hbg Haz MA From;
  0 41.2 211 142 99.9 114 110 !DC;
  41.2 0 196 181 146 154 100 !Alta;
  211 196 0 356 314 282 295 !Brd;
  142 181 356 0 56.1 54.5 116 !Berk;
  99.9 146 314 56.1 0 88.2 69.3 !Hbg;
  114 154 282 54.5 88.2 0 137 !Haz;
  110 100 295 116 69.3 137 0 ; !MA;
VCAP = 30;  ! Capacity of a truck 
DMAX = 500;  ! Max distance allowed on a route; 
MXTRK = 9999;  ! Max number of vehicles allowed; 
ENDDATA

SUBMODEL VROUTE:

! Minimize total travel distance;
MIN = TDIST;
TDIST = @SUM( CXC: DIST * X);

@FOR( CITY(k):
! a vehicle does not travel inside itself,...;
X( k, k) = 0;
);

! For each city, except depot....;
@FOR( CITY( k) | k #GT# 1:

! a vehicle must enter city K from some city I,...;
[NTR] @SUM( CITY( i) | i #NE# k #AND# ( i #EQ# 1 #OR#
Q( i) + Q( k) #LE# VCAP): X( i, k)) = 1;

! a vehicle must leave K after service to some city J;
[XIT] @SUM( CITY( j) | j #NE# k #AND# ( j #EQ# 1 #OR#
Q( j) + Q( k) #LE# VCAP): X( k, j)) = 1;

! U( k) is at least amount needed at K, but can't 
exceed vehicle capacity;
@BND( Q( k), U( k), VCAP);

! If K follows I, then can bound U( k) - U( i);
@FOR( CITY( i) | i #NE# k #AND# i #NE# 1:
[UL] U( k) >= U( I) + Q( k) - VCAP + VCAP *
( X( k, i) + X( i, k)) - ( Q( k) + Q( i))
* X( k, i);
);

! If K is 1st stop, then U( k) = Q( k);
U( k) <= VCAP - ( VCAP - Q( k)) * X( 1, k);

! If K is not 1st stop...;
U( k) >= Q( k) + @SUM( CITY( i) | i #GT# 1: Q( i) * X( i, k))
);

! Compute the total distance traveled by the vehicle through J;
@FOR( CITY( j):
[R_TD_1] TD( j) >= DIST( 1, j) X( 1, j);
@FOR( CITY( i) | i #GT# 1:
[R_TD] TD( j) >= TD( i) + DIST(i, j)X(i,j) - DMAX * ( 1 - X(i, j))
);

! Longest trip cannot exceed max trip length;
TD( 1) <= DMAX;
! Make the X's binary;
@FOR( CXC: @BIN( X));

! TMPM = time per mile,
TME(k) = earliest allowed arrival time at stop K,
TML(k) = latest allowed arrival time at K,
TMV(k) = stop or visit time at K,
TMAX = maximum time for any trip, e.g., 11 hrs in US;

! Time window related constraints;
@FOR( CITY(k) | k #GT# 1: 
  @FOR( CITY(i) | i #NE# k: 
    ! Time of arrival at K if preceding stop was I;
    [RTM] TMA(k) >= TMA(i) + ( TMV(i) + TMPM*DIST(i,k))* X(i,k) -TML(i)*(1-X(i,k));
    ! Must arrive within the [TME, TML] window. We are allowed
    ! in order to arrive no earlier than TME(k);
    @BND( TME(k), TMA(k), TML(k));
  );
)

! Max trip time constraint, assumes distance matrix
satisfies triangle inequality;
[XT] TMA(k) + TMV(k) + TMPM*DIST(k,1)*X(k,1) <= TMAX;
);

! Minimum no. vehicles required, fractional
and rounded up;
VEHCLF = @SUM( CITY( I)| I #GT# 1: Q( I))/ VCAP;
VEHCLR = VEHCLF + 1.999 -
@WRAP( VEHCLF - .001, 1);
! Must send enough vehicles out of depot;
@SUM( CITY( j) | j #GT# 1: X(1,j)) >= VEHCLR;

! Max vehicles\trucks constraint;
@SUM( CITY( j) | j #GT# 1: X(1,j)) <= MXTRK;
ENDSUBMODEL

CALC:

@SET( 'TERSEO', 1);  ! Make output somewhat terse;
@SET( 'IPTOLR', .01);  ! Relative optimality tolerance;
@SET( 'TIM2RL', 30);  ! Time to turn on IPTOLR in seconds;

@SOLVE( VROUTE);

ISTAT = @STATUS();

@IFC( ISTAT #EQ# 0 #OR# ISTAT #EQ# 4: ! Do report only if optimal or fea-
  sible;
    FW = 12;
    NROUTES = 0;
    @WRITE( @NEWLINE(2),' Vehicle Routing Trip Report',@NEWLINE(1),
      ' Total distance= ', TDIST);
    ! Write a listing of the routes;
    @FOR( CITY( j):
      @IFC( X( 1, j) #GT# .5: ! City j first on trip? ;
NROUTES = NROUTES + 1;
@WRITE( @NEWLINE( 2), 'ROUTE ', NROUTES, ':', @NEWLINE( 1));
@WRITE( ' FROM TO ARR TIME', @NEWLINE( 1));
@WRITE('----------------------------------------', @NEWLINE( 1));
@WRITE( '   FROM        TO            ARR TIME', @NEWLINE( 1));
@WRITE( '-------------------------------------', @NEWLINE( 1));
@WRITE( '   ', CITY( 1), (FW-@STRLEN( CITY( 1)))*' ',
      CITY( j), (FW-@STRLEN( CITY( j)))*' ',
      @FORMAT( TMA( j), '10.1f'), @NEWLINE( 1));
IPOS = J;
@WHILE( IPOS #NE# 1:
   NLOOPS = NLOOPS + 1;
   @FOR( CITY( J2): ! Which city J2 follows city IPOS? ;
      @IFC( X( IPOS, J2) #GT# .5:
         @IFC( J2 #NE# 1: ! Have we returned to depot? ;
            @WRITE( '   ', CITY( IPOS), (FW-@STRLEN( CITY( IPOS)))*' ',
                  CITY( J2), (FW-@STRLEN( CITY( J2)))*' ',
                  @FORMAT( TMA( J2), '10.1f'), @NEWLINE( 1)));
         @ELSE
            @WRITE( '   ', CITY( IPOS), (FW-@STRLEN( CITY( IPOS)))*' ',
                    CITY( 1), (FW-@STRLEN( CITY( 1)))*' ',
                    @FORMAT( TMA( IPOS) + TMV( IPOS) + TMPM * DIST( IPOS, 1),
                    '10.1f'), @NEWLINE( 1)));
      );
   IPOS = J2;
   @BREAK;
   );
);
Appendix C: LINGO Results

Delivery Route via Pure Cross-docking Strategy:

Global optimal solution found.

Objective value: 1445.000
Objective bound: 1445.000
Infeasibilities: 0.5684342E-13
Extended solver steps: 4911
Total solver iterations: 126760

Vehicle Routing Trip Report
Total distance= 1445

ROUTE 1:
FROM        TO            ARR TIME
-------------------------------------
UP          ALT             1000.0
ALT         BEAV            1800.0
BEAV        GA              1900.0
GA          UP              2059.6

ROUTE 2:
FROM        TO            ARR TIME
-------------------------------------
UP          BRD             2800.0
BRD         UP              3083.2

ROUTE 3:
FROM        TO            ARR TIME
-------------------------------------
UP          BERK            2933.2
BERK        HBG             3386.8
HBG         MA              3500.0
MA          UP              3662.0

ROUTE 4:
FROM        TO            ARR TIME
-------------------------------------
UP          WB              775.6
WB          WS              1500.0
WS          SCH             3000.0
SCH         HAZ             3600.0
HAZ         UP              3766.8
Delivery Route via Hybrid Cross-docking Strategy:

Global optimal solution found.

Objective value: 905.7000
Objective bound: 905.7000
Infeasibilities: 0.2842171E-13
Extended solver steps: 0
Total solver iterations: 311

Vehicle Routing Trip Report
Total distance: 905.7000000000001

ROUTE 1:

<table>
<thead>
<tr>
<th>FROM</th>
<th>TO</th>
<th>ARR TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>UP</td>
<td>ALT</td>
<td>1001.0</td>
</tr>
<tr>
<td>ALT</td>
<td>BRD</td>
<td>2800.0</td>
</tr>
<tr>
<td>BRD</td>
<td>UP</td>
<td>3083.2</td>
</tr>
</tbody>
</table>

ROUTE 2:

<table>
<thead>
<tr>
<th>FROM</th>
<th>TO</th>
<th>ARR TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>UP</td>
<td>HBG</td>
<td>1902.7</td>
</tr>
<tr>
<td>HBG</td>
<td>BERK</td>
<td>3000.0</td>
</tr>
<tr>
<td>BERK</td>
<td>HAZ</td>
<td>3600.0</td>
</tr>
<tr>
<td>HAZ</td>
<td>MA</td>
<td>3900.0</td>
</tr>
<tr>
<td>MA</td>
<td>UP</td>
<td>4062.0</td>
</tr>
</tbody>
</table>
Appendix D: Sample Purchasing Record Data

Vegetables & fruits for UP campus:

<table>
<thead>
<tr>
<th>Item Type</th>
<th>Average Unit Price ($/lb)</th>
<th>Average Order Quantity (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple Gala</td>
<td>1.12</td>
<td>40</td>
</tr>
<tr>
<td>Apple Gold 125</td>
<td>1.11</td>
<td>40</td>
</tr>
<tr>
<td>Apple Gold 64</td>
<td>1.16</td>
<td>120</td>
</tr>
<tr>
<td>Apple Granny Smith 100</td>
<td>1.30</td>
<td>160</td>
</tr>
<tr>
<td>Apple Granny Smith 64</td>
<td>1.45</td>
<td>120</td>
</tr>
<tr>
<td>Apple Red 100</td>
<td>1.15</td>
<td>40</td>
</tr>
<tr>
<td>Apple Red 125</td>
<td>1.10</td>
<td>520</td>
</tr>
<tr>
<td>Apple Red 64</td>
<td>1.09</td>
<td>40</td>
</tr>
<tr>
<td>Asparagus</td>
<td>2.84</td>
<td>40</td>
</tr>
<tr>
<td>Avocados</td>
<td>2.96</td>
<td>30</td>
</tr>
<tr>
<td>Baby Carrots 1 lb Bag</td>
<td>1.74</td>
<td>120</td>
</tr>
<tr>
<td>Baking Potato 100</td>
<td>0.99</td>
<td>250</td>
</tr>
<tr>
<td>Baking Potato 120</td>
<td>0.96</td>
<td>80</td>
</tr>
<tr>
<td>Baking Potato 90</td>
<td>1.01</td>
<td>40</td>
</tr>
<tr>
<td>Banana 10 #</td>
<td>0.51</td>
<td>20</td>
</tr>
<tr>
<td>Bananas 40 #</td>
<td>0.46</td>
<td>20</td>
</tr>
<tr>
<td>Basil</td>
<td>13.95</td>
<td>10</td>
</tr>
<tr>
<td>Blackberries</td>
<td>2.73</td>
<td>10</td>
</tr>
<tr>
<td>Blueberries</td>
<td>6.23</td>
<td>56</td>
</tr>
<tr>
<td>Bok Choy</td>
<td>0.83</td>
<td>30</td>
</tr>
<tr>
<td>Broccolo Head</td>
<td>1.50</td>
<td>110</td>
</tr>
<tr>
<td>Cabbage Chinese Napa</td>
<td>1.62</td>
<td>80</td>
</tr>
<tr>
<td>Cabbage Savoy</td>
<td>2.50</td>
<td>80</td>
</tr>
<tr>
<td>Cantaloupe</td>
<td>1.90</td>
<td>40</td>
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**Meats for the 12 campuses served by HFS (see Figure 1.1)**

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