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# Evaluating Warehouse Strategies for Two-Product Class Distribution Planning

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# **EVALUATING WAREHOUSE STRATEGIES FOR TWO-PRODUCT CLASS DISTRIBUTION PLANNING**

A thesis submitted in partial fulfillment of the  
Requirements for the degree of  
Master of Science in Engineering

By

**BRADLEY ROBERT GUTHRIE**  
B.S., Wright State University, 2013

2015  
Wright State University

WRIGHT STATE UNIVERSITY  
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October 1, 2015

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Bradley Robert Guthrie ENTITLED Evaluating Warehouse Strategies for Two-Product Class Distribution Planning BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Engineering.

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## **ABSTRACT**

Guthrie, Bradley Robert. M.S. Egr., Department of Biomedical Industrial and Human Factors Engineering, Wright State University, 2015. Evaluating Warehouse Strategies for Two-Product Class Distribution Planning.

Distribution networks often manage products with varying life-cycles, where demand for some products is relatively stable throughout the year (basic products) and the demand for others is short-lived (fashion products). Beyond the coordination of inventory and transportation decisions, decisions at the warehouse must be considered as its resources are frequently shared by both product classes simultaneously. For this two-product class distribution planning problem, we focus on characterizing three real-world distribution strategies observed in industry and evaluating them based on total distribution cost and warehouse measures (e.g., workforce plan and workload variation) against a benchmark ILS-based heuristic. Experimental results suggest that there are in fact strategies in industry that under specific system configurations may provide competitive solutions compared to the benchmark heuristic on large problem instances (e.g., 200 stores, 1000 products, 28 days). Several managerial insights are derived to compare such distinct warehouse strategies and the corresponding impact on the network.

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## 1. INTRODUCTION

Real-world distribution networks frequently manage distributing not just one, but multiple products, each with a distinct life-cycle. While the demand for some set of products may be steady throughout the year, the demand for others may only exist for a short amount of time (e.g., months, weeks). Based on their life-cycles, such products can be categorized into two main product classes: long (often referred to as basic or staple products) and short (also known as fashion products) (USOTA, 1987), with each product class comprising of a fairly large set of stock keeping units (SKUs); e.g., cell-phones and trend apparel (short life-cycle), and sugar and jeans (long life-cycle).

For long-life cycle products (*basic*, from here on), the relatively low variance of the demand patterns make it amenable for the distribution network to focus on developing plans that are cost effective. This is typically observed in many distribution planning models in the literature, which largely focus on a single-product class (with multiple SKUs in each class), such as the *inventory-routing problem* (Campbell et al., 1998; Kleywegt et al., 2004; Lin and Chen, 2008) and *production-inventory-distribution-routing problem* (Lei et al., 2006; Bard and Nananukul, 2008; Boudia et al., 2009). In contrast, for short-life cycle products (*fashion*, from here on), distribution plans are often aimed at providing maximum availability of products to consumers, by being due-date driven. General methods in literature describe this focus as “agile,” as opposed to “lean” for basic products (Bruce et al. 2004), and often focus more intently on pricing markdowns (Caro and Gallien, 2012), lead-time reduction (Mehrjoo and Pasek, 2015), and other attributes concerning the stochasticity that emerges from a fashion product’s short-life cycle. In general, no matter the product class, it is vital that the supply chain fit the product (Fisher, 1997).

While it is conceivable that distribution networks that handle multiple product classes may set up as sub-networks (i.e., a cost-effective sub-network for basic and a highly responsive (due-date driven) sub-network for fashion products), it is likely prohibitive from capital and coordination standpoints. What we have noticed having interacted with over 20 distribution networks during the last 10 years (many of which are Fortune 500 companies and/or leaders in their niche market), instead, is that companies adopt a single network through which both products classes must flow. Some degree of exclusiveness (or mild overlap) of vendors based on what they manufacture is reasonable; this allows for partial decomposition of the problem on the inbound transportation level. However, most networks rely on one or more warehouses for product consolidation/deconsolidation and possible value-added activities before delivering to the stores or through e-commerce channels. Significant challenges arise in such cases as these products classes tend to utilize similar resources (e.g., workers, loading docks, material handling equipment) at the warehouse.

We observed this very scenario at our industry partner's warehouse in the Midwest US. This US-based apparel distributor sells a wide variety of apparel (both basic and fashion) through its network of retail outlets and e-commerce channels. Their senior director of distribution indicated to us that because both basic and fashion apparel products from vendors across the globe simultaneously flow through this single warehouse, he is often faced with the arduous task of managing the warehouse resources on a daily basis (in particular, the workforce). Because of the inherent nature of the two products classes, where one class exhibits a relatively stable flow, while the other arrives in bursts, substantial workload variation results throughout the planning horizon. This has been a big concern when trying to hire temporary workers on a daily basis (over the already hired permanent workers) and dealing with their low productivity, and sometimes even adopting expensive transportation modes to avoid missing the due-date. These have negatively impacted the warehouse operating costs. To illustrate this point further, consider Figure 1 below that illustrates example inbound and outbound schedules of two basic ( $p_1, p_2$ ) and two fashion ( $q_1, q_2$ ) products over

a planning horizon (e.g., 1 month), assuming two vendors, one each for basic and fashion products, and a single store. Note that fashion product flow through the warehouse is restricted to only a portion of the planning horizon (*fashion horizon*). Arrows correspond to shipments (inbound, outbound) containing basic, fashion, or both product classes. Shaded areas in the warehouse represent hours associated with processing products from each class. In this instance, observe both  $p_1$  and  $q_2$  are shipped to the store individually, while  $p_2$  and  $q_1$  are combined on a single outbound shipment.

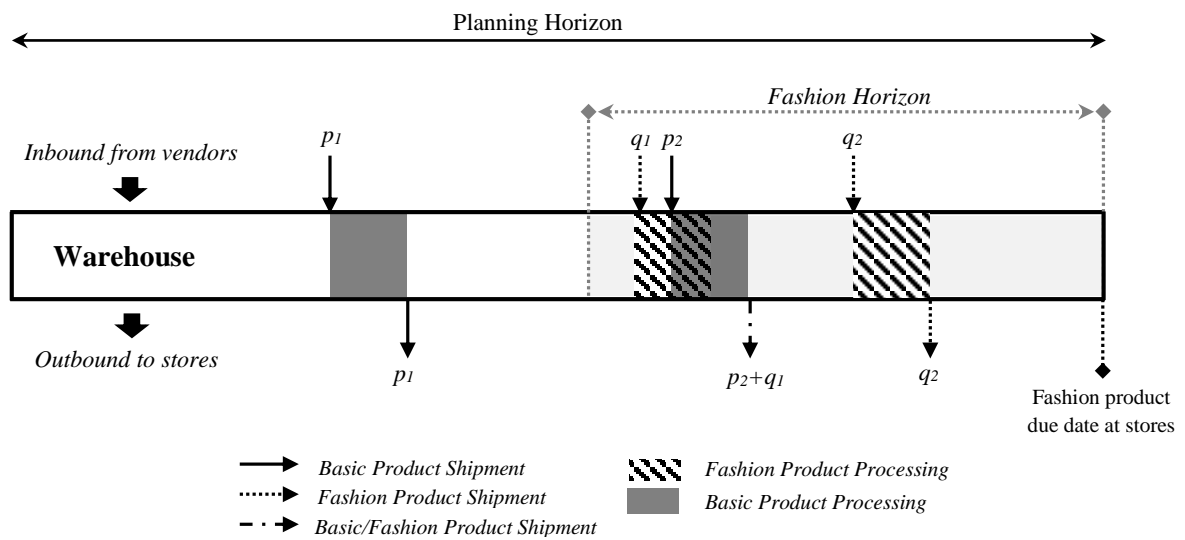


Figure 1. Integrated distribution network of fashion and basic products.

To address these challenges, an integrated two-product class distribution optimization problem, and an iterative-local search (ILS) based metaheuristic to generate near-optimal solutions to industry sized problems (e.g., 200 stores, 1000 products, and 28 days) have recently been proposed (Sainathuni et al., 2015). However, the ILS-based approach has weaknesses (similar to other metaheuristics) that limit its real-world implementation; e.g., long run time, solution variability, sensitivity to model inputs, difficult to explain, require significant cultural shift (Donati et al., 2008; Grosche, 2009; Talbi, 2009; Siberholz & Golden, 2010; Bhattacharya, 2013). We, in

fact, have witnessed our industry partner (and several other companies we have interacted with) develop their own strategies to address such challenging problems. Such strategies tend to be simple, quick, implementable, and robust, all of which have been pointed out in literature as important criteria for successful industry implementation (e.g., Barr et al., 1995; Viana et al., 2005; Gu et al., 2007; Teytaud and Vazquez, 2012; Borenstein and Moraglio, 2012; Bartz-Beielstein and Preuss, 2014). For instance, our industry partner has implemented two distinct warehouse strategies in the last three years to deal with the two-product class distribution problem. There have been, however, serious discussions in their organization on the relative benefits of one strategy over the other without much consensus yet.

This real-world observation motivated us to ask the following questions: *so which warehouse strategy employed in the industry is the best? How close is it to the known best solution for a given problem?* We address these questions by characterizing and evaluating several real-world strategies associated with the apparel industry. We specifically consider Fashion Release, Fashion Holding, and Basic-Fashion Split as they have either been implemented or considered by our industry partner. Each of these strategies is modeled and simulated to solve industry-sized problem instances. The corresponding results are benchmarked against a previously developed and validated ILS-based metaheuristic, which we further generalize and refer to it as the Fashion Window strategy. In summary, the key contributions of our research include the following:

- first-ever characterization of several real-world distribution strategies for two product classes, in a multi-period, multi-echelon setting;
- evaluating their performance against the benchmark Fashion Window strategy on several measures (e.g., total distribution cost, warehouse workforce plan, and workload variation);
- identifying attributes of the problem that suggest if one strategy is better than the others under specific conditions; and

- present several managerial insights to assist industry practitioners to appreciate the complex relationship between warehouse, inventory, and transportation decisions.

We anticipate that academics and industry practitioners would benefit equally from this research. Academics may be encouraged further to not only evaluate similar such strategies in domains other than apparel that deal with two or more product classes, based on either life-cycle or other characteristics (e.g., food, electronics), but also devise simple, quick, implementable, and robust strategies derived from the optimization models -- an important criteria for industry. Industry practitioners, on the other hand, would benefit from quantitatively benchmarking their current strategy (or alternatives being discussed) against optimization-based approaches proposed in the literature. This is expected to bridge a perceived gap between academic research and industry practice.

With this agenda, we organize the remainder of this paper as follows: Section 2 provides an overview of literature focused on warehouse approaches to two-product class distribution. Section 3 characterizes three real-world strategies and the approach we took to simulate them in our study. Section 4 provides experimentation results and discussion, while Section 5 contains sensitivity analysis of model parameters. We conclude in Section 6 with managerial insights and discussion of further research.

## 2. RELEVANT LITERATURE

We first summarize the literature in the area of warehouse and briefly highlight key distribution planning models that either depict the warehouse as a node, or account for some decisions therein. We follow with a review of literature pertaining to the distribution of fashion products.

Warehouse literature is quite broad and exhaustive, where the focus has ranged from warehouse location to design to operational planning. A broad review of this literature can be found in several recent reviews (Baker and Canessa, 2009; Gu et al., 2010). Recently, Staudt et al. (2015) have discussed literature pertaining to performance measures in warehouse.

Although the role of warehouses in overall distribution planning has been acknowledged (Lambert et al., 1998; Tan 2001; De Koster et al., 2007), they have often not been integrated in corresponding decision-making models. Most distribution models assume the warehouse as a node; e.g., the *inventory-routing problem* (Campbell et al., 1998; Kleywegt et al., 2004; Lin and Chen, 2008), the *integrated inventory-distribution problem* (Abdelmaguid and Dessouky, 2006), the *production-inventory-distribution-routing problem* (Lei et al., 2006; Bard and Nananukul, 2008; Boudia et al., 2009) and others considering inventory and transportation decisions (Parthanadee et al., 2006; Çetinkaya et al., 2006; Zhao et al., 2008; Çetinkaya et al., 2009). Only recently have models been proposed that integrate warehouse decisions alongside inventory and transportation; e.g., the *warehouse-inventory-transportation problem* (Sainathuni et. al., 2014). Such integrated approaches have shown substantial benefits in not only total distribution cost savings, but also obtaining a relatively balanced workload at the warehouse allowing warehouse managers to plan

and manage their workforce effectively. Note that these distribution planning models have largely focused on basic products.

A parallel stream of research has emerged that primarily focuses on fashion products, in particular inventory replenishment. Fisher et al. (2001) offer a heuristic that focuses on minimizing lost sales, backorders, and out-of-date inventory by determining fashion product replenishment order quantities. Weng and McClurg (2003) discuss the effect of coordination between suppliers and buyers when considering uncertain demand and delivery time. Patil et al. (2010) examine quantity discounts and transportation costs with respect to procurement, pricing, and transportation decision making.

Further, a growing number of distribution networks follow the approach coined as “fast fashion,” which entails quickly delivering the latest trends in fashion, at affordable prices (Cachon and Swinney, 2011; Caro and Martínez-de-Albéniz, 2015). Caro and Gallien (2010) design a mixed-integer optimization model considering inventory and transportation decisions to maximize overall predicted sales across all Zara (Spain-based leader in fast fashion) stores. Improvement following implementation ranged from 3% to 4%. Cagliano et al. (2011) utilize system dynamics simulation to analyze warehouse management around fast fashion products. Their findings suggest potential value when utilizing more reliable (but expensive) vendors, outsourcing operations, and allowing more flexibility in worker levels. Recently, Mehrjoo and Pasek (2015) discuss risks in a quantitative manner that come natural to fast fashion distribution networks. Lead time and delivery delay were both found to significantly impact risk, and therefore supply chain performance.

While it is alluded to in literature that distribution networks must accommodate the unique life-cycles of their products (Aitken et al., 2003), we have not found any research that considers both the flow of both basic and fashion products, as well as the resulting complexities that emerge at the warehouse level, with the exception of Sainathuni et. al. (2015); as discussed in section 1. Further, while real-world distribution networks we have interacted with have employed various strategies at their warehouse based on insights from some combination of their prior experience or



internal analysis, there has been no clear way to inform decision makers in industry of the quality of solutions from such strategies. It then becomes critical to benchmark these industry strategies against optimal or near-optimal approaches.

Realizing this gap between the academic literature and industry practice, we reiterate the focus of this research as follows: characterize real-world warehouse strategies for a two-product class distribution problem, benchmark them against the best available solution for large problem instances generated by an ILS-based metaheuristic, identify network attributes for which a certain strategy performs better than the others, and derive managerial insights. We now detail a few prominent real-world warehouse strategies we have noticed, especially at our partnering apparel distribution company, and subsequently characterize them.

### **3. CHARACTERIZING REAL-WORLD WAREHOUSE STRATEGIES**

Although it is the norm for fashion and basic products to arrive at the warehouse separately, most warehouse activities to handle these product classes from the inbound until shipping at the outbound are alike. Besides certain activities that may be product-specific; e.g., quality check, special handling, or even kitting, most other activities for these two product classes are similar and handled by the same warehouse resources (i.e., workers, material handling equipment). They may further share the same storage space, and may even get consolidated on the same outbound shipment destined to a specific store on a given day – a situation similar to our industry partner. Effective management and coordination of all such warehouse activities is, therefore, crucial.

Currently, the Senior Director of distribution at our industry partner manages both product flow and workforce scheduling decisions using experience and intuition. By gradually unloading and proactively loading trailers over a number of days, he has demonstrated proficiency in partially alleviating the variation in daily workload at the warehouse. While in his role his primarily focus has been on efficiently coordinating the necessarily warehouse activities, he realizes that coordination with the company's transportation and inventory teams is vital if true benefits in terms of cost are to be realized throughout the overall distribution network. Through discussions with him, as well as other observations from our industry experiences, we realized that there are strategies that exist in industry which serve as general rules of managing the numerous decisions explained above. Further, we have found the most popular strategies to be those that contain a single parameter, as they are easy to interpret and implement. We propose a way to model three of the prominent real-world warehouse strategies, and also compare them to a generalized benchmark

(near-optimal) strategy, all of which are summarized briefly in Table 1 below. Note that all three industry-based strategies contain only a single parameter.

Table 1. The four strategies evaluated for the two-product class distribution planning problem.

Strategy	Parameter(s)	Brief Description
Fashion Release	$R$	All fashion products are shipped $R$ days following their inbound day (plus processing time)
Fashion Holding	$H$	All fashion products are shipped $H$ days before their due date (minus lead time to store)
Basic-Fashion Split	$t_{split}$	Warehouse processing of basic and fashion products occurs in two distinct sequential windows
Fashion Window (Benchmark)	$R, H$	All fashion products are shipped outbound in a window beginning $R$ days after their inbound day (plus processing time) and ending $H$ days before their due date (minus lead time to store)

Before presenting details of these four strategies, we first summarize how the features and decisions comprised in the two-product class distribution planning problem are modeled in our study.

Product class and planning horizon: Let  $P$  and  $Q$  be the sets of basic and fashion products (each composed of distinct quantities), respectively, with product indexes  $p \in P$  and  $q \in Q$ . Each product is delivered by a specific vendor ( $v \in V$ ) and is shipped to a store ( $s \in S$ ). The planning horizon during which all processes occur at the warehouse is denoted as  $t = 1, 2, \dots, T$ , where  $T$  is the length of the planning horizon in days. We refer to the portion of the planning horizon during which fashion products arrive, are handled, and eventually shipped out of the warehouse as the *fashion horizon*. The beginning day of this horizon is designated as  $t_q^b$ , the end day for inbound shipments as  $t_q^e$ , and the due date of fashion product  $q$  at store  $s$  is  $t_{sq}^y$ . The end day ( $t_q^e$ ) is calculated by the due date ( $t_{sq}^y$ ) minus the maximum lead time across all stores ( $Max\{L_S\}$ ), minus the processing time of products in the warehouse ( $pt$ ). Within the fashion horizon, there are distinct windows that designate the feasible range for inbound and outbound shipments. We will discuss these with respect to each strategy individually later in this section. Further, the expected demand for basic and fashion products at each store during each time day is assumed to be known in advance.

Warehouse activities: While the activities at the warehouse are quite complex and interleaved, we take an aggregate approach given the relative focus of the distribution planning we consider; more towards tactical and less operational. With this idea, we use ‘putaway’ to represent all the activities that are involved from unloading, staging, and eventual putaway to the appropriate storage location. Similarly, we use ‘picking’ to include actual picking, sorting, staging, and loading (see Figure 2). Not treating the warehouse as a node in the distribution network (similar to previous work) and accounting for several operational details (albeit at some aggregate level) enables us to evaluate the interaction between warehouse, transportation, and inventory decisions, simultaneously for both basic and fashion products.

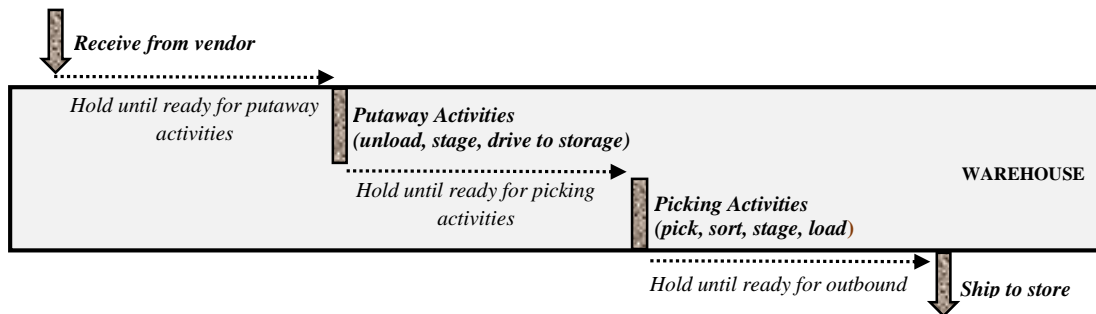


Figure 2. Pictorial representation of product flow through the warehouse.

Warehouse workforce: It is also imperative to generate an efficient plan for the warehouse workforce. Based on the common theme derived from our interactions with several warehouse managers, two worker types (at the minimum) can be noticed; permanent and temporary. Permanent workers are similar to full-time workers with a 40-hr work week, fairly skilled at performing a variety of activities at the warehouse, and are often salaried (with or without additional benefits). Temporary workers are typically hired on a daily basis for  $\leq 8$  hours, may not have the same productivity levels as the permanent workers (as they often are unfamiliar with the layout, processes, and material handling equipment), and are paid hourly. These workers are frequently

utilized as a way to manage variations in worker hours at the warehouse, more often during the fashion horizon.

We refer to  $\alpha$  and  $\beta_t$  to denote the number of permanent (required throughout the planning horizon) and temporary workers (required during a specific day,  $t$ ), respectively. The associated costs are denoted as  $C^a$  and  $C^b$ , in \$/hr. Worker rates in items/hr are split based on warehouse activity, with  $A_{put}$  referring to an aggregate rate for all putaway activities, and  $A_{pick}$  likewise for picking. Because in a real-world setting, most warehouse managers prefer to use a mix of permanent (higher skilled, but higher cost) and temporary (lower skill, but lower cost) workers, we use  $\gamma$  to represent the maximum allowable proportion of permanent workers that can be employed as temporary workers. That is, if there are 20 permanent workers and  $\gamma = 0.5$ , then no more than 10 temporary workers could be hired during a given day,  $t$ . Further, because the hired temporary workers may not be identical across days when needed (depending on the availability at the third-party that provides such workers), we can attach a productivity rate ( $\phi$ ) for each temporary worker, where if  $\phi = 1$ , then a temporary worker's productivity is the same as a permanent worker; if  $\phi = 0.8$ , then a temporary worker exhibits a 20% reduction in their productivity.

Inventory and transportation: Also included in the scope of our model are inventory and transportation decisions, and their associated costs. Inventory decisions are considered distinctly at the warehouse, and across all stores, for both basic and fashion products. The day starting from when a product arrives on an inbound shipment at the warehouse until that product departs on an outbound shipment denotes holding time at the warehouse. Holding time at a store begins once an outbound shipment arrives at a store, and ends on the day of demand for that product (basic) or the due date (fashion). We let  $C_p^h$  ( $C_{sp}^h$ ) represent the holding cost of basic products  $p$  (fashion products  $q$ ) at the warehouse (store  $s$ ) in \$/item/day, and  $C_q^h$  ( $C_{sq}^h$ ) likewise for fashion products.

We also consider in our model the transportation shipments (inbound to and outbound from the warehouse) and associated costs for each day. To model inbound transportation we consider an

inbound network with designated vendors supplying either basic or fashion products. On the outbound side, however, each store is expected to have demand for both product classes, which may cause consolidation of the two product classes on a shipment to a specific store when possible. We utilize a cost structure proposed in Sainathuni et al. (2014), which is composed of a fixed cost of a shipment and variable costs based on both distance (between source and destination) and weight of the shipment.

Decisions, objective function, and constraints: The joint decisions to be made across both product classes include warehouse workforce (permanent and temporary), inbound shipment schedule from vendors, outbound shipment schedule to stores, and inventory levels at the warehouse and stores. The objective function is to minimize total distribution cost, which includes warehouse (picking + putaway), inventory (stores + warehouse), and transportation (outbound + inbound). Key constraints include meeting the store demand for basic products each day, not violating the fashion product due date, ensuring temporary workers are no more than the allowable limit, and non-splitting of fashion shipments.

We now discuss the 4 strategies, summarized in Table 1, in further detail.

### **3.1 Fashion Release (FR)**

A specific instance of the Fashion Release (FR) strategy is what our industry partner has adopted at their warehouse, largely driven by their current CEO who hails from the fashion industry. The primary focus at this distributor has been towards best managing the flow of fashion products, with the flow of basic products managed as usual. Essentially, their FR strategy is set up such that as soon as a fashion product  $q$  arrives from the vendor to the warehouse, and after incurring some processing time ( $pt$ ) at the warehouse, all quantities of  $q$  will be shipped to each store with associated demand in the following day. The company leadership suggested that in so doing, they may possibly gain benefits at the store; e.g., avoiding a spike in workload at the stores due to large shipments coming in on, or just before the due date. This strategy was debated internally because

of possible drawbacks such as increased inventory cost at the stores and possible opportunity loss during outbound shipment consolidation to stores.

We generalize this specific version of our industry partner’s strategy by introducing a parameter  $R_q$ , which denotes the number days (beyond processing time) after which fashion product  $q$  must be shipped from the warehouse to the corresponding stores. The value of  $R_q$  is bounded between 0 and the length of the fashion outbound window given by  $(t_{sq}^y - t_q^b - pt - L_s)$ , where  $t_{sq}^y$  is the due date for product  $q$  at store  $s$ ,  $t_q^b$  is the beginning of the fashion horizon,  $pt$  is the processing time at the warehouse, and  $L_s$  is the lead time to store  $s$ . The outbound day of product  $q$  can then be determined by  $t_q^o = t_q^l + pt + R_q$ , with the inbound day ( $t_q^l$ ) constrained as  $t_q^b \leq t_q^l \leq t_q^e - R$ . If the warehouse chooses to use a single value for each fashion product  $q$ , then  $R=R_q \forall q$ .

In short, the FR strategy is driven by the *inbound day of fashion products*, and focuses on structuring the flow of fashion products by *releasing* them to stores as *early* as desired; the smaller  $t_q^b$  value of  $R$ , the quicker the release from the warehouse.

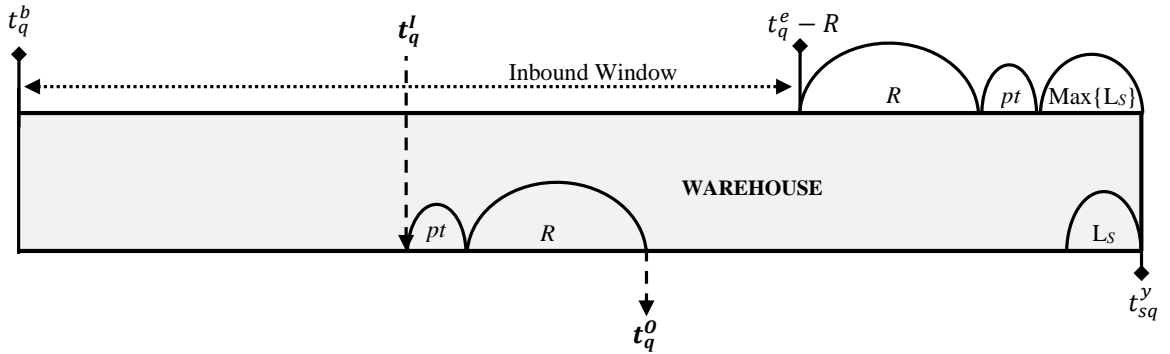


Figure 3. Illustration of bounds for Fashion Release.

### 3.2 Fashion Holding (FH)

The Fashion Holding (FH) strategy takes inspiration from the same industry partner’s former distribution strategy, directed by their former CEO who had served in a leadership role at a leading US retailer of both basic and fashion products. According to this strategy, the arriving fashion products are held at the warehouse until the latest possible day of shipment to their corresponding

stores (accounting for the lead time). The core concept was to change the look of the stores overnight, in sync with the beginning of a new fashion season. The implications of this from a distribution planning sense were varied. Holding fashion products until close to the due date increased the number of opportunities for consolidation on outbound shipments, as well as lowered inventory levels at stores. However, sudden spikes in scheduled outbound shipments from the warehouse led to greater difficulties in managing workforce, often leading to not meeting the demand or using a higher cost transportation mode (e.g., overnight air). Further, this also resulted in higher costs at the stores in terms of receiving all fashion shipments on one day and remodeling the store overnight.

We generalize this strategy by incorporating a parameter  $H_q$ , which represents the number of days prior to its due date (considering lead time) that product  $q$  must be shipped outbound. Similar to  $R_q$  in FR,  $H_q$  is also bounded by 0 and  $(t_{sq}^y - t_q^b - pt - L_s)$ , and can be represented by  $H = H_q, \forall q$  as applicable. The outbound day of product  $q$  going to store  $s$  is determined by  $t_{sq}^o = t_{sq}^y - L_s - H$ . Similar to FR,  $t_q^b \leq t_q^l \leq t_q^e - H$ .

In short, the FH strategy is driven by the *due date of fashion products*, and focuses on structuring the flow of fashion products by *holding* them at the warehouse as *long* as desired; small values of  $H$  hold until close to the due date at the store (accounting for lead time).

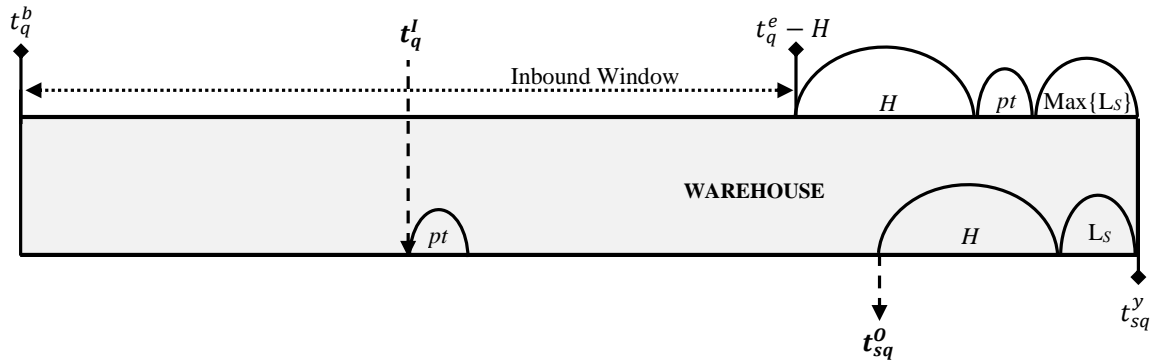


Figure 4. Illustration of bounds for Fashion Holding.



### 3.3 Basic-Fashion Split (BFS)

Another strategy that was discussed with our industry partner, but not implemented yet, was to separate the flow of basic and fashion products along the horizon; we refer to as the Basic-Fashion Split (BFS) strategy. That is, depending on the anticipated number of fashion products (and the associated product quantities) the warehouse may manage the flow of all the basic products earlier in the horizon and dedicate its efforts on managing the flow of fashion products later in the horizon. The idea is that if an appropriate split of the horizon were found, then the warehouse workload variation could be mitigated to some extent, possibly reducing warehouse worker cost. However, this reduction was thought to have negative implications via increased inventory levels of basic products at stores.

To evaluate the BFS strategy, we let  $t_{split}$  represent the day that splits the planning horizon into two sub-horizons, one each for basic and fashion. We determine the value of  $t_{split}$  using the demand proportion of the basic products to the total demand; i.e.,  $t_{split} = \frac{\sum_{s \in S, p \in P, t \in T} D_{spt}}{(\sum_{s \in S, p \in P, t \in T} D_{spt} + \sum_{s \in S, q \in Q, t \in T} D_{sqt})} * T$ , where  $D_{spt}$  ( $D_{sqt}$ ) refers to the demand of basic (fashion) product  $p$  ( $q$ ) at store  $s$  in time  $t$ , and  $t_q^b \leq t_{split} \leq t_q^e$  (split day cannot be outside of the fashion horizon). Figure 5 below graphically shows how  $t_{split}$  determines the division of basic and fashion horizons.

In short, as opposed to structuring the flow of fashion products as in FR and FH, the BFS strategy focuses on *modifying the feasible windows for basic and fashion products* with respect to associated *product quantities*.

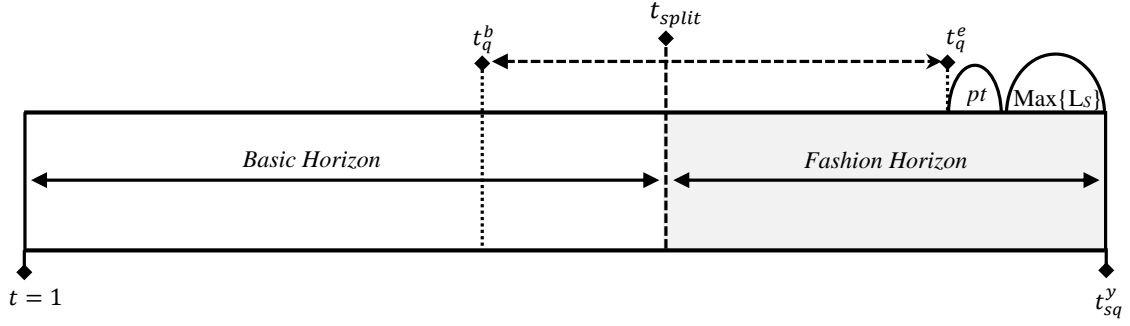


Figure 5. Illustration of bounds for Basic-Fashion Split.

### 3.4 Fashion Window (FW)

In order to adequately benchmark the three strategies discussed above, we devised the Fashion Window (FW) strategy. The intuition was that specifying an outbound window for fashion products, as opposed to assigning an exact outbound day as exhibited by  $R$  in FR and  $H$  in FH, would expand the solution space, likely increasing the possibility of finding a near-optimal (if not optimal) distribution plan for benchmarking purposes.

The FW strategy is an enhanced version of the ILS-based heuristic proposed recently in Sainathuni et al. (2015). The key enhancements include (i) a generalization via two parameters,  $R$  and  $H$  and (ii) additional internal variables to allow flexibility in how long products can stay in inbound trailers until they are putaway, and for products waiting in outbound trailers prior to departure. Enhancement (ii) allowed us to more closely model the real system at our industry partner's warehouse; we included this enhancement in the previous three strategies as well. Additional improvements include refinements to the initial solution to generate a good initial feasible solution (instead of purely random) and an additional initial stage of improvement and perturbation for only basic products prior to main flow of the ILS heuristic.

Figure 6 shows a schematic of the FW strategy at the warehouse. Let  $t_q^{EO}$  and  $t_{sq}^{LO}$  represent the earliest and latest outbound days. Accordingly,  $t_q^{EO} = (t_q^I + pt) + R$  and  $t_{sq}^{LO} = (t_{sq}^y - L_s) - H$ ; the outbound window for fashion products then becomes  $[t_q^{EO}, t_{sq}^{LO}]$ . Similar to FR and FH, the fashion

inbound window must adjust accordingly with  $R$  and  $H$ , where  $t_q^b \leq t_q^l \leq t_q^e - H - R$ . Individually, and as a sum, both  $R$  and  $H$  are both bounded by  $t_{sq}^y - t_q^b - pt - L_{Max}$ .

In short, the FW strategy is driven by both *the inbound day of fashion products* and their respective *due dates at stores*, and aims to structure the flow of fashion products through the warehouse by *modifying their feasible inbound and outbound windows*.

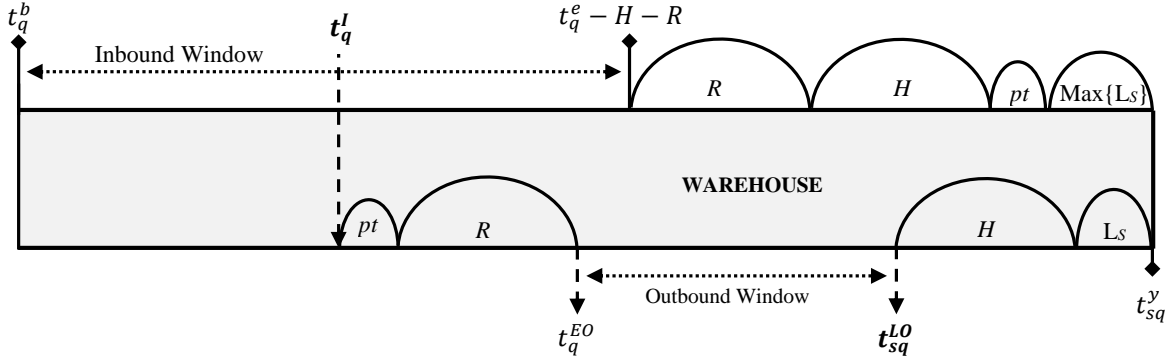


Figure 6. Illustration of FW bounds for fashion inbound and outbound windows.

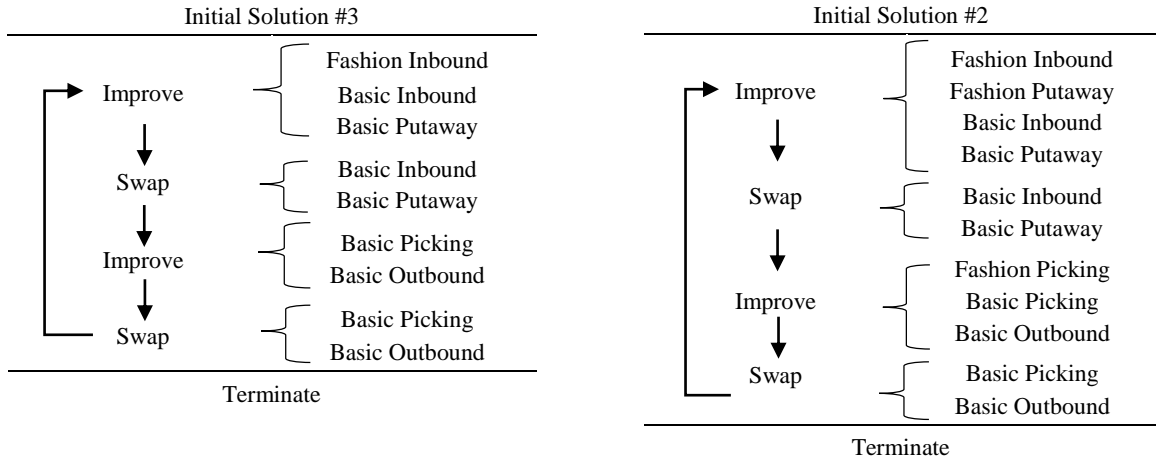
Intuitively,  $R = H = 0$  would provide the widest window for fashion outbound, and is expected to return lowest cost solutions. However, with wider windows, solutions are much harder to obtain, understand, and likely difficult to implement in real practice compared to solutions provided via tighter windows or specific date (as preferred by our industry partner). We explore the impact of  $R$  and  $H$  values on solution quality in Section 5.2.

### 3.5 Simulating the Four Strategies

Each strategy was simulated using a strategy-specific initial solution, followed by a unique set of local search and perturbation moves that modify the quantity of product  $p(q)$  on day  $t$  scheduled for inbound, putaway, picking, and outbound. Table A.1 (in Appendix A) summarizes the initial solutions and moves used when simulating the strategies. Each description provides the source day (SD) of the move (day that product quantities are moved from), the destination day (DD) of the move (day that product quantities are moved to), and also the type of move employed. The unique

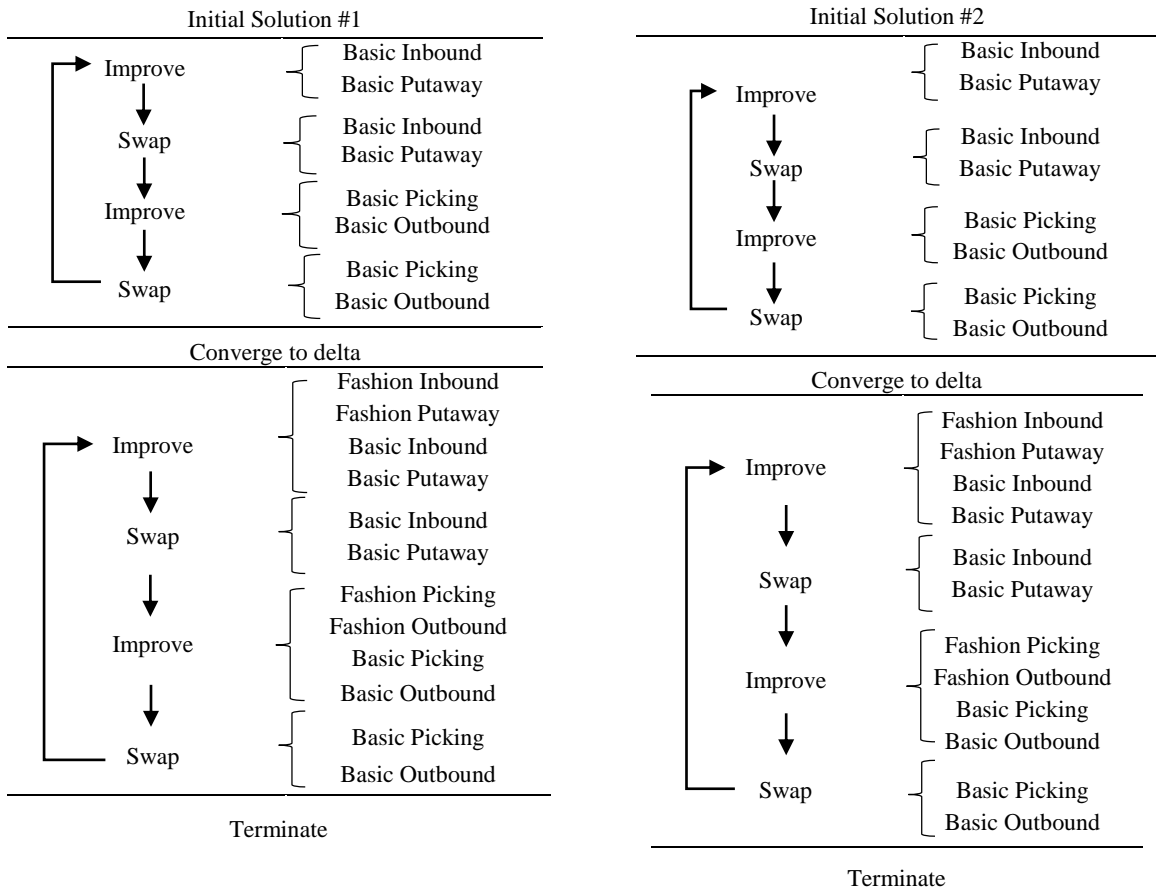
sequence of moves for each strategy are summarized in Figure 7. The four strategies were coded in C#.

We briefly explain how the FW strategy is simulated referencing Figure 7(d); the three other strategies are simulated in a similar way. The algorithm for the FW strategy uses an initial solution similar to FH, where the basic solution is randomized and the fashion solution schedules all fashion product SKU's to be shipped outbound to stores at the latest possible day considering lead time. The algorithm begins by holding the schedule of all fashion products static, and only modifies the schedule of basic products, through local search (improve) and perturbation (swap) moves, until convergence. The algorithm then freely alters both basic and fashion solutions, and terminates upon a second convergence. The convergence factor is set at  $5 \times 10^{-9}$  in order to successfully provide a benchmark solution; for all other strategies a value of 0.0025 was found sufficient.



**(a) Fashion Release**

**(b) Fashion Holding**



**(c) Basic-Fashion Split**

**(d) Fashion Window (Benchmark)**

Figure 7. Complete set of moves and initial solutions required to simulation the four strategies.

## 4. EXPERIMENTAL EVALUATION OF THE STRATEGIES

To benchmark the distribution plans and total costs generated by the three strategies against the benchmark FW strategy, we conducted a detailed experimental study. All problem instances were industry-sized comprising of 20 vendors (10 for fashion and 10 for basic), 200 stores, 1000 products, and 28-day planning horizon.

Other specific parameter settings were as follows. The lead time from the warehouse to stores ranged from 0 to 2 days. We set processing time at the warehouse ( $pt$ ) to 1 day. The due date ( $t_{sq}^y$ ) was set to day 28  $\forall s, q$ ; as such the end time ( $t_s^e$ ) computed to day 25  $\forall s$ . We set both  $R$  and  $H$  equal to 0, the parameters for the FR and FH strategies, respectively; for the FW strategy,  $R=H=0$  as well. Warehouse parameters  $\gamma$  (maximum temporary/permanent workers) and  $\phi$  (temporary worker productivity rate) were 1 and 0.8 respectively. The putaway rate was 1200 items/hr, which was determined based on a stacking frames pallet storage system, counter balance lift trucks for pallet retrieval, and radio frequency (RF) technology. The picking rate was 200 items/hr and assumed carton flow racks and RF technology. Holding costs were set at 0.01 and 0.05 \$/item/day for all products at the warehouse and stores, respectively. We now present our findings, both at aggregate and detailed levels.

### 4.1 Comparison of Total Costs

We first assessed total distribution cost by day for a single problem instance in order compare the three strategies against the FW strategy. Figure 8 displays the problem instance with the above parameter settings and permanent worker cost of \$15, temporary worker cost of \$10, a product mix

ratio of 1:1 (i.e., ratio of total number of basic products to total number fashion products), and a 2-week fashion horizon within a 4-week planning horizon.

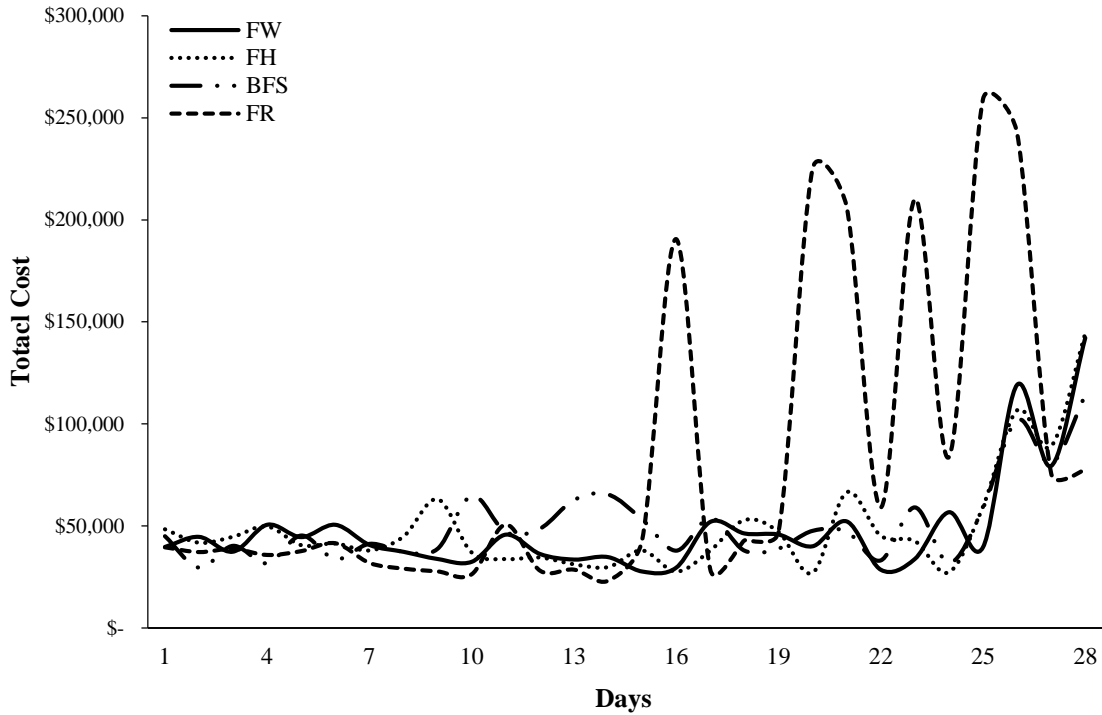


Figure 8. Comparison of total cost per day.

Notice that in days prior to the fashion horizon (days 1-14), all strategies demonstrate roughly similar, stable, patterns of cost. This seems intuitive given that only basic products are handled during those days (with relatively steady demand). However, once the fashion horizon begins, the FR strategy noticeably distinguishes itself from the other strategies as evident by the relatively high spikes in total cost. Since fashion products must leave the warehouse exactly 1 day after their arrival under this strategy, not only is inventory across stores intensified, but there is also a lack of flexibility in consolidating outbound shipments, and balancing putaway and picking hours. In this specific problem instance, each of the 200 stores requires at least 1 fashion product from each of the 10 fashion vendors. Consequently, for each day with an inbound shipment of fashion products, there are 200 corresponding outbound shipments the following day to the stores. This in

turn results in relatively high warehouse costs due to all associated putaway and picking hours being constrained to inbound and outbound shipment days respectively.

Looking at the other three strategies during the fashion horizon, their total costs for each day remain relatively stable until the final three days where they all show a sharp increase. Because lead time to stores ranges from 0 to 2 days, these days represent the last possible outbound dates for fashion products to the corresponding stores. The FH strategy, given its constraint of  $H=0$  (hold until the last possible day), schedules only 1 outbound shipment containing fashion products to each store throughout the fashion horizon (all of which occur during the final 3 days), resulting in a high degree of outbound consolidation. Further, the store inventory is relatively lower given the shipments to the stores are so close to the due date. A less obvious benefit of this consolidation approach is the impact on warehouse costs. Given the ability to disperse warehouse hours for handling fashion products over a time span greater than 1 day (starting from the inbound day until the outbound day), as opposed to FR, the FH strategy results in 57% lower warehouse costs. In this instance, we note that the FW and BFS strategies also mimic the consolidating structure of the FH strategy.

We further observe that the resulting total costs for the FR, BFS, and FH strategies in figure 8 are 36%, 6%, and 5% higher than the benchmark FW strategy, respectively.

## **4.2 Warehouse Cost Contribution**

To understand the impact of warehouse decisions on total cost, we evaluated the total warehouse cost as a percentage of total distribution cost for 10 different instances for each policy, varying product mix (5 levels, x-axis) and worker cost (2 levels, dark and light lines) as shown in Figure 9. The fashion horizon was assumed to be 2 weeks in a 4-week planning horizon.



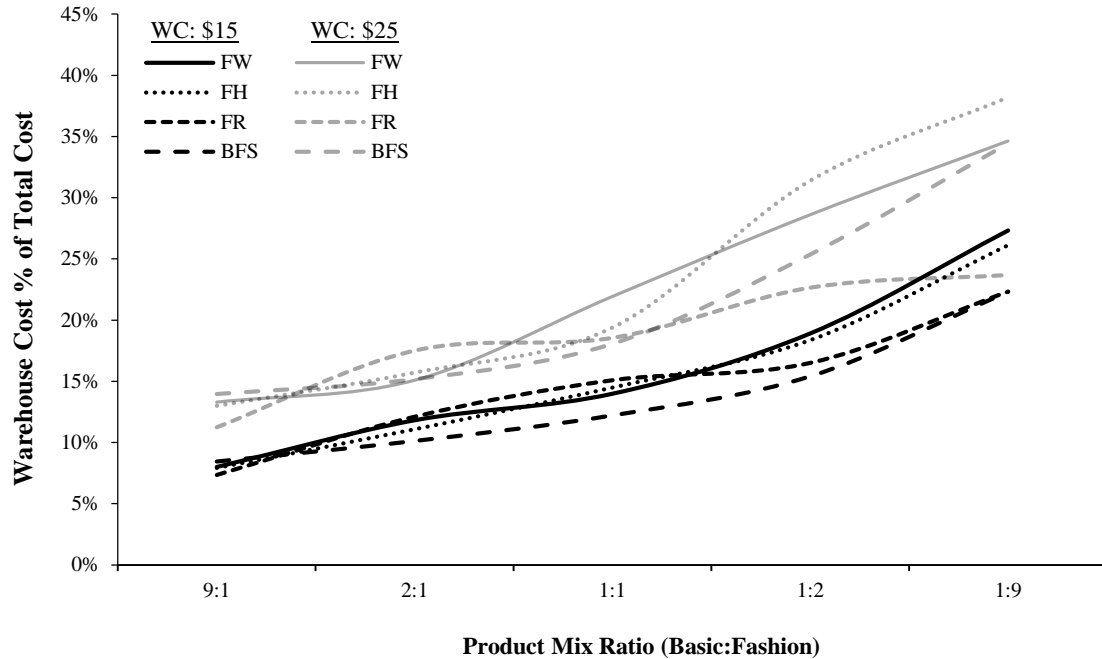


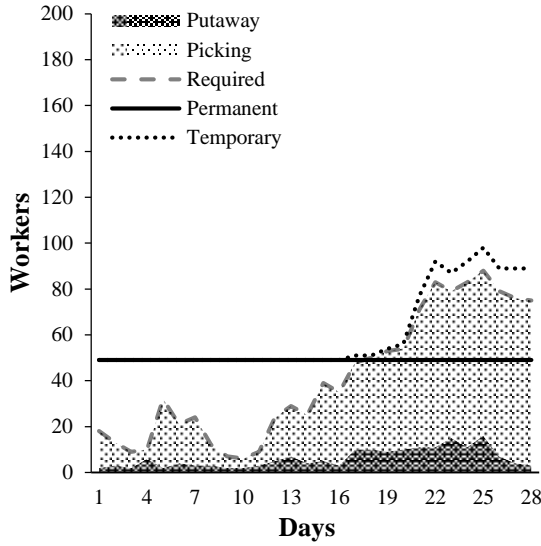
Figure 9. Comparison of warehouse cost contribution to total cost.

The two key takeaways here are the range and magnitude of warehouse cost contribution values. For each policy, there is a general trend of increasing percentages as the product mix ratio shifts toward more fashion products. This can be partially attributed to the changing proportion of fashion products that are required to be processed during the fashion horizon. For a product ratio of 9:1, only 10% of all products have this requirement, as opposed to a product ratio of 1:9 where that number jumps to 90%. With 90% of total product quantity flowing through the warehouse during only 50% of the planning horizon, a relatively high variation in the workload is realized, resulting in increased warehouse costs. Further, a decreasing product mix ratio means that there are fewer basic products in the distribution network, resulting in lower inventory levels (warehouse and stores) that typically spread throughout the planning horizon, as well as a reduced number of supporting outbound shipments. Thus, increasing warehouse costs, along with decreasing inventory and transportation costs, results in a substantial increasing trend in warehouse cost contribution, with ranges for FW resulting in 8-27% and 13-35% for worker costs of \$15 and \$25, respectively.

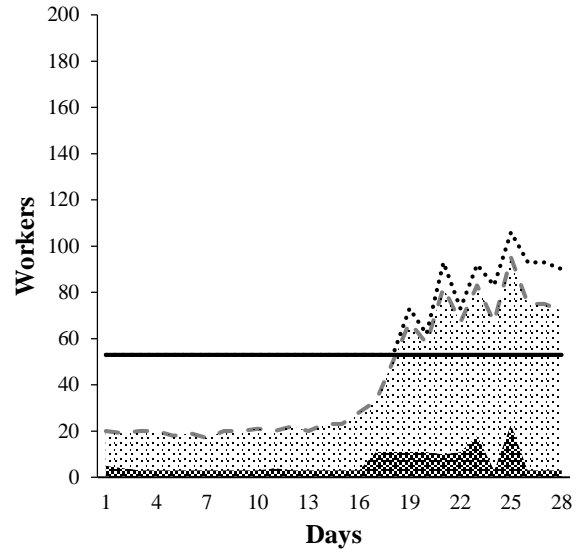
As expected, increasing the worker cost generally resulted in an increase in warehouse contribution across all product mix ratios, with differences up to 13%. With the exception of the FR strategy, increased worker costs do not have a substantial effect of the structure of distribution plans generated by the other 3 strategies (FW, FH, and BFS); i.e., the inventory and transportation costs were relatively stable. As many distribution/supply chain managers tend to write off warehouse costs as insignificant compared to inventory and transportation costs, the findings here argue that warehouse costs can comprise up to 28% or 38% of total distribution costs, which is substantial.

### **4.3 Warehouse Workforce Plan**

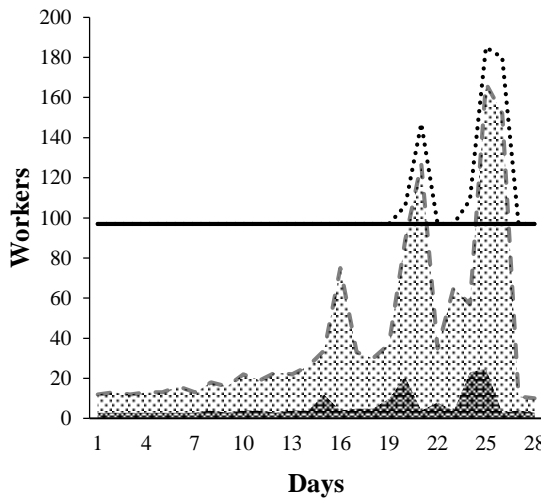
Having evaluated the warehouse cost contributions at an aggregate level, which could be significant, we now focus on analyzing the workforce plan generated by these strategies. For this, we consider a product-mix ratio of 1:1, 2-week fashion horizon, and cost of permanent (temporary) workers as \$15/hr (\$10/hr) to compare scheduling of workers in the warehouse for each policy. Figure 10 shows the workforce plan generated by each of the 4 strategies for this problem instance. ‘Permanent’ and ‘temporary’ refer to the number of workers scheduled by type. ‘Required’ represents the actual number of workers (equivalent of permanent workers) required during that day; we further break it down by activity type (‘putaway’ and ‘picking’).



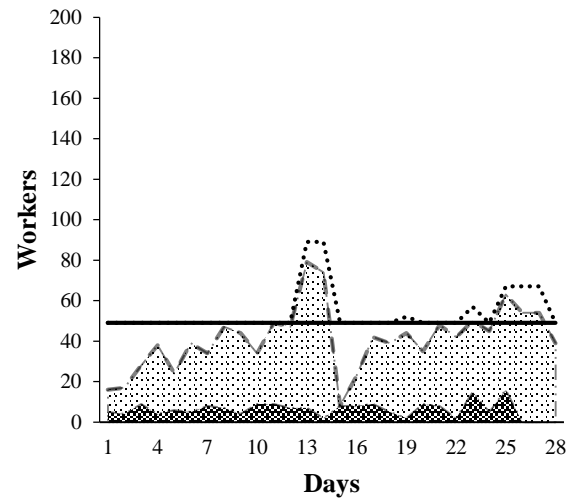
(a) Fashion Window



(b) Fashion Holding



(c) Fashion Release



(d) Basic-Fashion Split

Figure 10. Workforce plans generated by the 4 strategies.

From the figure, it is clear that FW, FH, and FR exhibit similar behavior in workforce planning (i.e., temporary workers only in the fashion horizon), while the structure of BFS noticeably differs (i.e., temporary workers throughout the planning horizon). As predicted, BFS results in a relatively balanced required workload, leading to a permanent worker identical to that of FW (49).

While FH is close behind (55), FR produces a considerably higher level (97) due to its poor ability to balance worker hours. Considering the utilization of temporary worker levels, we note that all 4 strategies take full advantage of temporary workers during peak days, limited only by the  $\gamma$  parameter, as these workers are relatively inexpensive (\$10/hr vs. \$15/hr for permanent).

For each of the 4 strategies, the permanent worker line passes above the required worker line, which suggests idle time for such workers. This is not surprising, and commonly observed in industry, where workers would then be assigned miscellaneous tasks such as cleaning of work areas, reorganization, and other supporting activities. In our experiments, this effect is attributed to a pre-specified value of  $\gamma$  (maximum allowable temporary workers) equal to 1.0, which means that whenever temporary workers are required during a given day, their number is bounded by the level of the permanent workers (for the entire planning horizon). Thus, the permanent worker level must be adjusted to account for the maximum number of workers required over the entire planning horizon.

We further verified through additional experiments (not shown), a higher value of  $\gamma$  would lead to lowering the permanent worker line closer to the ‘required’ line alleviating some idle time; a lower value of  $\gamma$  has the opposite effect. While some warehouses may prefer a higher  $\gamma$  – we know at least two such warehouses –, certain others may not prefer this due to increased training and likely errors if most of the temporary workforce is not the same from one day to another.

Also observe that the ‘required’ line (which represents permanent equivalent workers) is always below the ‘temporary’ worker line as temporary worker productivity parameter,  $\phi$ , is set at 0.8; the two lines will align when  $\phi = 1.0$ .

#### **4.4 Variation in Total Worker Hours**

We now analyze the variation in the worker hours, from which the above workforce plan was derived, to further understand how the 3 strategies compare against the benchmark FW strategy. We represent workload variation by calculating the %-difference of worker hours required during

each day from the average warehouse hours (across the planning horizon). The graph below displays the range of such values for each strategy, over 5 instances (varying product mix ratio).

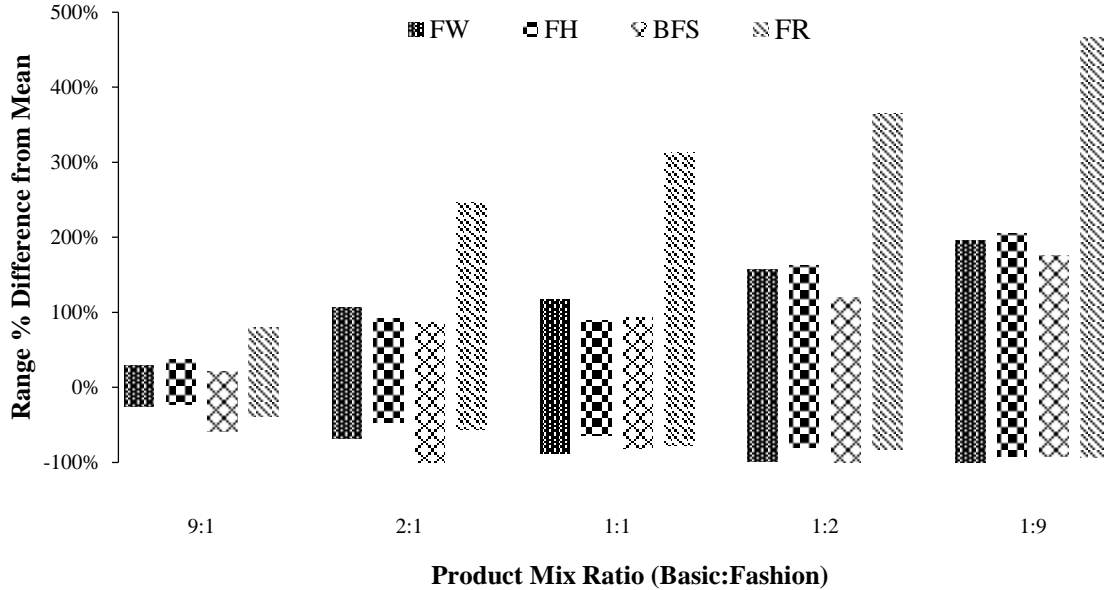


Figure 11. Variation in total warehouse hours across various product mix ratios.

From Figure 11, we notice that all strategies demonstrate an increasing trend of variation with a decreasing product mix ratio. This is intuitive as the more the basic products, the more opportunities there are to effectively balance the workload at the warehouse; an observation similar to Sainathuni et al., 2014. However, with the inclusion of fashion products, which have a strict due date and must be handled in a reasonably short time-frame, the variation in the workload is expected to increase.

We notice further that the FR strategy demonstrates considerably higher sensitivity to product mix ratio than the other strategies, again due to fashion warehouse hours being constrained to their respective inbound and outbound days. For a ratio of 1:9, FR results in an absolute difference from FW of 267%, compared to a value of 63% for a 9:1 ratio. Also, we note that the FW, FH, and BFS strategies alternate in providing the smallest range among the 4 strategies across the considered

product mix ratios. As pointed out earlier, a higher degree of workload variation at the warehouse greatly deters the planning of workforce at the warehouse, often leading to underutilized worker hours or not enough workers, both leading to higher costs and/or affecting service downstream.

## 5. SENSITIVITY TO SYSTEM PARAMETERS

Having analyzed and compared the quality of distribution plans generated by the 3 strategies with the benchmark FW strategy at an aggregate cost perspective and detailed warehouse level, we now discuss how sensitive these solutions are to changes in system parameters. We first analyze the impact of varying product mix ratio, fashion horizon length, and worker costs for all strategies, and proceed with displaying how the values of  $R$  and  $H$  affect the FW strategy for various product mix ratios.

### 5.1 Sensitivity to System Parameters

Table 2 below contains the parameters, along with their associated number of levels and values. This resulted in 20 scenarios we evaluated using each of the 4 strategies; i.e., a total of 80 experiments. Figure 12 displays for each combination the ratio of each strategy's total cost to that of the Fashion Window strategy. Also displayed is the total cost (in \$) of the FW strategy for each parameter combination.

Table 2. Parameters varied in experiment and their respective number of levels and values.

Parameter	Levels	Values
Product mix ratio (basic:fashion)	5	1:9, 2:1, 1:1, 1:2, 1:9
Fashion horizon length (weeks)	2	1, 2
Permanent(temporary) worker cost (\$/hr)	2	\$15(\$10), \$25(\$20)

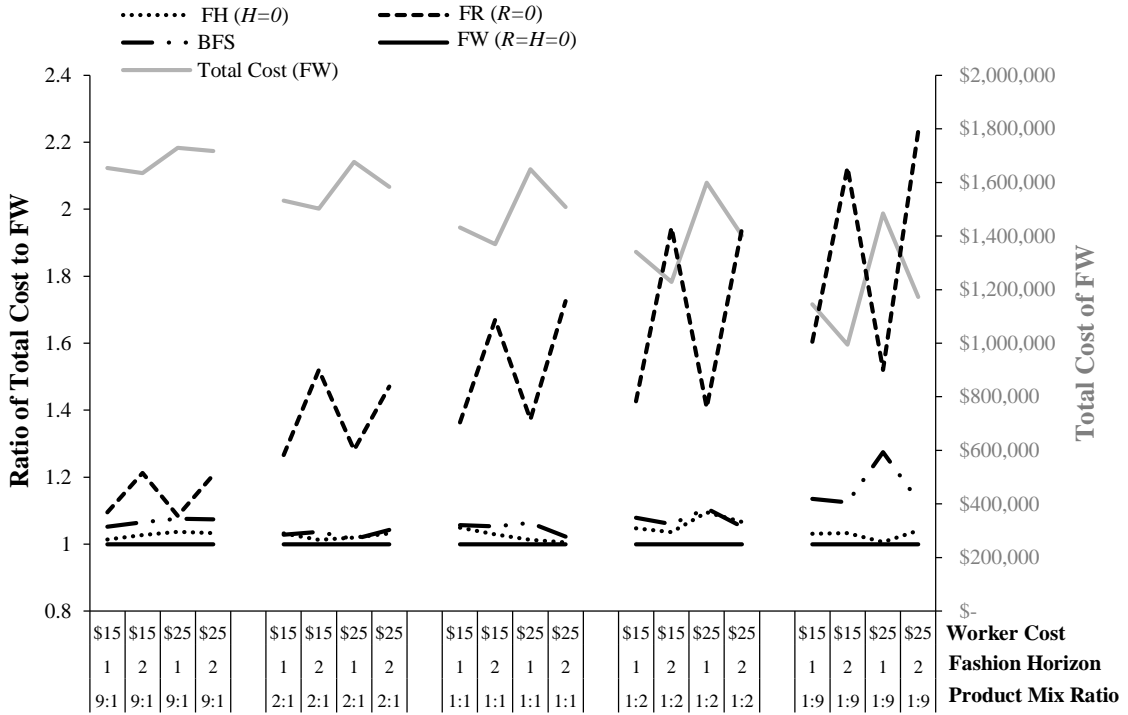


Figure 12. Sensitivity of total cost (relative to FW) to product mix ratio, length of fashion horizon, and worker cost.

Focusing on the cost ratios for each strategy, we note that the FH strategy performs fairly well over all parameter combinations, consistently within 10% (1.1 times) of the FW strategy. As previously indicated, the approach of holding all fashion products until their last possible shipment date benefits both outbound consolidation and store inventory levels, as well as contributes to relatively low variation in warehouse hours.

In contrast, the FR strategy behaves much worse than FW (1.08 – 2.23), more prominently as the product mix ratio reduces. This finding can be associated with our earlier observations that the FR strategy provides little opportunity for consolidation of fashion products on the outbound side, as well as a poorly balanced workload. Note that a tighter fashion horizon length (1 vs. 2 weeks) has a positive impact on the FR strategy performance largely because there are naturally more consolidation opportunities across a shorter horizon than longer.



Similar to the FR strategy, the BFS strategy displays an increasing total cost ratio, but not as drastic, for a decreasing product mix ratio; ranging from 1.01 – 1.27 times of the FW strategy. We note that for BFS, at minimum 2 shipments must be sent from the warehouse to each store, one carrying only basic products during the initial part of the planning horizon, and the other carrying only fashion products during the latter part. For a larger proportion of basic products (e.g., 9:1), this constraint does not separate BFS too far from FW (1.05 – 1.08). However, as the product mix ratio decreases, FW tends to schedule a declining number of outbound shipments (as low as 1 shipment per store), increasing the separation of BFS from FW up to 1.27. Further, it is also for lower product mix ratios where increasing the length of the fashion horizon improves the performance of BFS relative to FW (due to relatively lower warehouse costs). All 6 instances of a 2-week fashion horizon for product mix ratios 1:1 through 1:9 resulted in improved performance over their 1-week counterpart, with a range of .3% - 11.4%.

A summary of general trends for the total cost ratio of each strategy relative to the FW strategy is presented in Table 3, along with the trends in total distribution cost for FW. Upward and downward arrows indicate an increase and decrease in cost ratio accordingly, while a “-” represents no apparent trend. Note that FH is the only strategy that is robust compared to FW for all parameters, while worker cost has no distinct effect on the total cost ratio of each strategy.

Table 3. General trends of strategy total cost ratio and FW total cost sensitivity to parameters.

<i>With an increase in the ...</i>	<i>(a) the total cost of FW:</i>	<i>(b) the total cost with respect to FW:</i>		
		<b>FR</b>	<b>FH</b>	<b>BFS</b>
<b>Proportion of fashion products (decreasing product mix ratio)</b>	↓	↑	-	↑
<b>Fashion horizon length</b>	↓	↑	-	↓
<b>Worker cost</b>	↑	-	-	-

As displayed in the above table, we note the decreasing nature of total cost for the FW strategy (gray lines in figure 12) as product mix ratio decreases (more fashion). The intuition is that

with more fashion products flowing through the warehouse, there is considerably more variation in the warehouse workload (as illustrated in Section 4.4), thus increasing warehouse costs. Though found to be true, per our discussion of warehouse cost contribution, lower product mix ratios also result in decreased store inventory levels, as well as decreased outbound shipments, offsetting the warehouse cost increase; in fact, lowering the total cost.

Run times associated with each strategy was were also recorded in the above experiments, as quickness is one of the attributes of strategies we discussed to be favored by decision makers in the industry. Selected results and associated discussion can be found in Appendix B.

## **5.2 Sensitivity to $R$ and $H$ Parameters**

All preceding experiments were run with the parameters in the FW strategy,  $R$  and  $H$ , set to 0. This was done to allow for the largest possible search space in order to obtain a benchmark (near-optimal) solution to the distribution problem for comparison purposes. However, the FW strategy in itself can result in a number of variations based on the specific values of  $R$  and  $H$ . We, therefore, analyzed 10 additional variations of the FW strategy and compared them against the benchmark (i.e.,  $R=H=0$ ) in order to understand the effect of the length of fashion inbound and outbound windows on total cost. For each of the 5 product mix ratios, we calculated the ratio of the total cost for each combination of  $R$  and  $H$  to that obtained for  $R=H=0$ . The length of the fashion horizon is 2 weeks and worker cost is set to \$15/hr for permanent and \$10/hr for temporary.

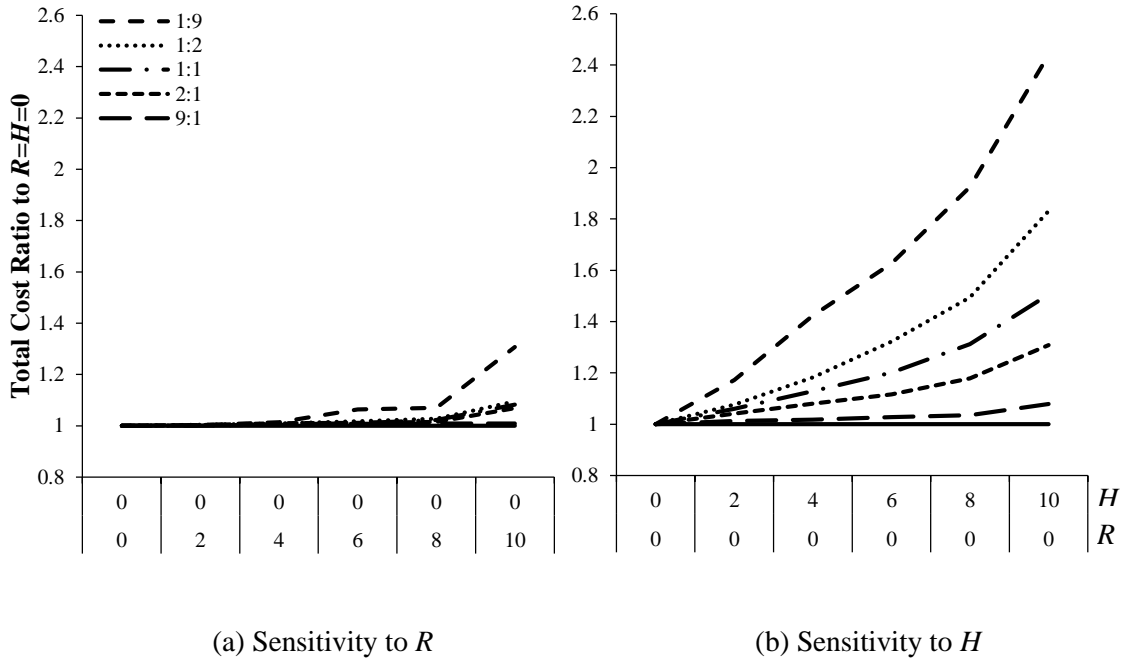


Figure 13. Total cost sensitivity of FW to the two parameters: (a)  $R$  and (b)  $H$ .

Figure 13 presents the total cost ratio comparisons where we first analyzed the sensitivity of the FW strategy to  $R$  (for  $H=0$ ) and then to  $H$  (for  $R=0$ ), across all 5 product mix ratios. This helped us evaluate which of the two parameters appeared to affect the solution quality substantially. The solid black line with total cost ratio equal to 1.0 represents the ratio of  $R=H=0$  variation to itself.

Two key observations can be made. First, the FW strategy is significantly more sensitive to increases in the value of  $H$  (which shrinks the fashion horizon from the tail end) than increasing  $R$  (which shrinks it from the front end). For instance, in the case of a product mix ratio of 1:1, increasing  $R$  from 0 to 10 with  $H=0$  (Figure 13(a)) increases the cost ratio to 1.05 (5% increase) while increasing  $H$  from 0 to 10 with  $R=0$  (Figure 13(b)) suggests an increase to 1.52 (52% increase). This can be explained by realizing that when  $H=10$ , the inbound window is now limited to just 1 day (at  $t_q^b$ , day 15) and the outbound window is limited to just 3 days (days 16, 17, 18). As a result, both picking and putaway warehouse costs are significantly affected (due to the lack of

days to distribute warehouse hours), along with store inventory costs (i.e., fashion products arrive 10 days prior to their due date (day 28)).

Second, the magnitude of trends differs for each product mix ratio. Consider the  $R=0$  and  $H=10$  combination in Figure 13(b). In this case, while the total cost for the product mix of 9:1 (more basic, less fashion) is only 1.08 that of  $R=H=0$ , this ratio is 2.42 for the product mix of 1:9 (less basic, more fashion). This difference in cost ratios between product mix ratios becomes prominent for higher values of both  $R$  and  $H$ . This is intuitive because both  $R$  and  $H$  determine the boundaries for the fashion inbound and outbound windows. Shrinking these windows (by either increasing  $R$  or  $H$  or both) will have a growing detrimental effect on the total cost as the proportion of fashion products increases.

## 6. CONCLUSIONS AND FUTURE RESEARCH

Most distribution networks are challenged with effectively and efficiently managing the flow of two or more classes of products with differing life cycles. For a specific two-product class distribution problem, we focused on evaluating various warehouse strategies that decision makers in the industry have implemented. We considered the case of apparel distribution given our close ties with one in the Midwest US distributors. For such multi-period, multi-echelon, distribution networks we identified and then characterized 3 warehouse strategies (i.e., Basic-Fashion Split, Fashion Release, and Fashion Holding) and compared them against our benchmark ILS-based heuristic (referred to as the Fashion Window strategy). Several measures were used, such as total distribution cost, warehouse workforce plan, and workload variation. The following managerial insights were drawn from our study:

- Fashion Holding (FH) strategy appears to generate distribution plans very close to the benchmark FW strategy; typically within 5% and at max 10% higher. Holding fashion products until their latest possible outbound day increases the potential for outbound shipment consolidation, reduces store inventory levels, and increases the opportunity for workload balancing. These findings are robust to all realistic combinations of parameters we experimented with in our study; see Figure 12. The BFS strategy, while for lower product mix ratios (9:1 – 1:2) also performs close to FW (1–9% higher), it becomes less competitive for a ratio of 1:9 (8–27%).
- The FR strategy is somewhat competitive for high product mix ratios (more basic, less fashion), but its performance also deteriorates with an increase in the number of fashion

products. Essentially, shipping fashion products out to the stores relatively quickly (upon inbound at the warehouse) tends to result in missed opportunities for consolidation of outbound shipments, increased store inventory levels, and less flexibility for warehouse balancing.

- The percent contribution of warehouse cost to the total distribution cost increases with a higher proportion of fashion products. The benchmark strategy (FW) resulted in contributions ranging from 8% - 27% and 13% - 35% for worker costs of \$15(\$10) and \$25(\$20) respectively; similar trends were observed for the other 3 strategies (see Figure 9).
- From a workforce planning perspective, the BFS strategy generated an identical level of permanent workers as the FW strategy; FH created a level 8% higher, followed by FR at 98% (see Figure 10). Further, the required workload of BFS was generally balanced across the planning horizon, while that of other strategies was heavily skewed toward the fashion horizon (i.e., 50.6% of the total required workload for BFS occurred in the fashion horizon, compared to 79.2% for FW).
- Variation of total warehouse hours increases with a higher proportion of fashion products (see figure 11). FH and BFS perform close to, if not better than FW across all product mix ratios, while FR displays a significant amount of sensitivity for increasing values (63% to 267% absolute difference in range from FW)

A few other observations based primarily of the solutions from the benchmark FW strategy are worth noting. The total distribution cost decreases with a higher proportion of fashion products. While counterintuitive, the corresponding decrease in store inventory levels and increase in consolidation of outbound shipments outweigh the increased cost of warehouse workers (caused by higher workload variation); see Figure 12. Additionally, the effect of the parameter  $H$  (which shrinks the fashion outbound window from the tail end) on total cost is far greater than the effect

of  $R$  (which shrinks it from the front end); see Figure 13. Essentially, if a narrower outbound window were required or preferred from a warehouse standpoint, then it is beneficial, from a total cost perspective, to shorten the outbound window of such products from the front end while holding the tail end static, as opposed to doing the other way round.

The implications of our findings can be significant. The quantification of how such strategies compare to benchmark approaches proposed by academics (e.g., the FW strategy in this case) can provide industry practitioners deeper understanding and insights into the impact of their chosen strategy on warehouse, inventory, and transportation decisions. Of note, our industry partner had employed the FH strategy in the past, and is currently employing the FR strategy – two entirely distinct strategies. Our findings suggest that, purely from a distribution planning perspective, what they did in the past seemed to be far better in terms of total cost than what they are doing currently. When we shared our findings with them, they were intrigued as this was not what they expected, and are in discussions with us to further understand these findings. As managing multiple product classes is becoming a norm for modern day distribution networks, it is crucial to benchmark strategies adopted by industry that aim at dealing with this challenge, against optimization-based approaches developed by academics.

There are many possibilities for future research. Splitting shipments (inbound and outbound) is often practiced, and thus the resulting impact on inventory levels (warehouse and stores) and corresponding workload (putaway and picking activities) is intriguing. Further, the FH strategy requires the stores to receive and restock in a very short period of time, which can be challenging, and may have further cost implications. Also, the length of exposure of fashion products at the store and product pricing are obviously key factors if the objective is total revenue. Accounting for these would provide for an even more comprehensive understanding and comparison of these strategies.

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## APPENDIX A

Table A.1 Complete set of moves and initial solutions required to simulation the four strategies.

Initial Solution Name	Description of the Initial Solution
Initial Solution #1	Random Solution, Feasible to Basic-Fashion Split Calculation
Initial Solution #2	Random Solution, Feasible to Fashion Holding Outbound Constraint
Initial Solution #3	Random Solution, Feasible to Fashion Release Outbound Constraint
Move Name	Description of the Move
Improve Fashion Inbound	<b>SD:</b> Random <b>DD:</b> Random <b>Type:</b> Advance & delay shipments; putaway, picking, outbound moves to obtain feasibility
Improve Fashion Putaway	<b>SD:</b> Maximum required putaway workers <b>DD:</b> Minimum required putaway workers <b>Type:</b> Advance & delay putaway hours; picking move to obtain feasibility
Improve Fashion Picking	<b>SD:</b> Random <b>DD:</b> Minimum required picking workers <b>Type:</b> Advance & delay picking hours
Improve Fashion Outbound	<b>SD:</b> Random <b>DD:</b> Random <b>Type:</b> Consolidate Shipments
Improve Basic Inbound	<b>SD:</b> Random <b>DD:</b> Random <b>Type:</b> Consolidate Shipments
Improve Basic Putaway	<b>SD:</b> Maximum required putaway workers <b>DD:</b> Minimum required putaway workers <b>Type:</b> Split basic putaway hours
Improve Basic Picking	<b>SD:</b> Maximum required putaway workers <b>DD:</b> Minimum required putaway workers <b>Type:</b> Split basic picking hours
Improve Basic Outbound	<b>SD:</b> Random <b>DD:</b> Random <b>Type:</b> Consolidate Shipments
Swap Basic Inbound	<b>SD:</b> Random <b>DD:</b> Random <b>Type:</b> Swap all basic inbound shipments between days for a random number of vendors
Swap Basic Putaway	<b>SD:</b> Random <b>DD:</b> Random <b>Type:</b> Swap all basic putaway hours between days for a random number of vendors
Swap Basic Picking	<b>SD:</b> Random <b>DD:</b> Random <b>Type:</b> Swap all basic picking hours between days for a random number of stores
Swap Basic Outbound	<b>SD:</b> Random <b>DD:</b> Random <b>Type:</b> Swap all basic outbound shipments between days for a random number of stores

## APPENDIX B

Run times associated with each strategy were recorded in the experiments from section 5.1, as quickness is one of the attributes of strategies we discussed to be favored by decision makers in the industry. Table 5 below shows the average run times (HH:MM:SS) across 4 instances (varying worker cost and fashion horizon length) for the extreme product mix ratios we considered in this study (i.e., 1:9 and 9:1). Run times for all other ratios fell within these ranges. An Intel-i7 Quad-Core Desktop with 16 GB of RAM was used for experiments.

Table B.1 Average run times of strategies for product mix ratios of 1:9 and 9:1.

Strategy	Product Mix Ratio - 1:9	Product Mix Ratio - 9:1
FH	00:41:47	04:47:51
FR	00:34:55	07:34:40
BFS	00:50:36	14:56:01
FW	17:51:35	72:13:16

While the FH and FR strategies alternate in producing the lowest average times for the product mix ratios analyzed, the average values for BFS are considerably longer. This makes sense considering BFS has no structured fashion solution as in FR and FH. Note that the distribution planning problem is usually tactical in nature, such run times are fairly reasonable in industry; typically, such decisions are made once every few months and the algorithms are allowed to run overnight to achieve the best possible solution.

Also note that in order to obtain the best possible (near-optimal, if not optimal) solution from the FW strategy, the stopping criterion (tolerance based) was kept very small, and so the higher run times.