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Innovative Applications of O.R.

The warehouse-inventory-transportation problem for supply chains

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ABSTRACT

Warehouses play a vital role in mitigating variations in supply and demand, and in providing value-added services in a supply chain. However, our observation of supply chain practice reveals that warehousing decisions are not included when developing a distribution plan for the supply chain. This lack of integration has resulted in a substantial variation in workload (42–220%) at our industry partner's warehouse costing them millions of dollars. To address this real-world challenge, we introduce the warehouse-inventory-transportation problem (WITP) of determining an optimal distribution plan from vendors to customers via one or more warehouses in order to minimize the total distribution cost. We present a nonlinear integer programming model for the WITP considering supply chains with multiple vendors, stores, products, and time-periods, and one warehouse. The model also considers worker congestion at the warehouse that could affect worker productivity. A heuristic based on iterative local search is developed to solve industry-sized problems with up to 500 stores and 1000 products. Our experiments indicate that the distribution plans obtained via the WITP, as compared to a sequential approach, result in a substantial reduction in workload variance at the warehouse, while considerably reducing the total distribution cost. These plans, however, are sensitive to aisle configuration and technology at the warehouse, and the level and productivity of temporary workers.

1. Introduction

Modern supply chains rely heavily on warehouses for rapidly fulfilling customer demand through retail, web-based, and catalogue channels. Warehousing costs in 2010 were nearly \$112 billion across 600,000 small and large warehouses in the U.S., which is over 9% of the \$1.2 trillion of the U.S. logistics cost (CSCMP, 2011). Warehouses, now often referred to as distribution centers (DCs), have emerged from their traditional passive role of serving as buffers to mitigate supply-demand variations to a more active role of providing value-added services such as consolidation/deconsolidation, assembling, and kitting. The operations of Amazon.com illustrate the importance of careful warehouse management in modern supply chains (Curtis, 2013).

From a warehousing perspective, the key functions are (i) receiving, quality control, and putaway/storage and (ii) picking, sorting, packing and shipping (Tompkins, White, Bozer, & Tanchoco, 2010). To accomplish these functions, effectively making decisions around warehouse design and operations is vital. Some of these decisions include aisle layout, material handling selection, workforce planning and scheduling, and information technology infrastructure. These decisions have a significant bearing on the warehouse's throughput and cost, and impact other supply chain decisions such as inventory and transportation. For example, a new picking technology such as pick-to-light or robotic picking (e.g., Kiva robots) that alters (actually, improves) worker productivity may mean that inbound and outbound shipment schedules, along with inventory requirements at the warehouse, would be modified due to this change in the warehouse's throughput.

This research was motivated by the current practice of distribution planning, specifically at our industry partner, a US-based apparel supply chain. This supply chain sells to consumers through retail and e-commerce channels. Their warehouse, the only one in the supply chain, manages the flow of 6500–8000 products supplied by over 100 domestic and overseas vendors, and replenishes over 300 retail stores situated in nearly 40 states across the nation. Although this warehouse serves as a hub in the supply chain, it operates in a reactive mode; that is, inventory and transportation plans are determined first and the warehousing plans are determined later. This sequential approach results in the warehouse experiencing substantial variation in daily workload, which causes

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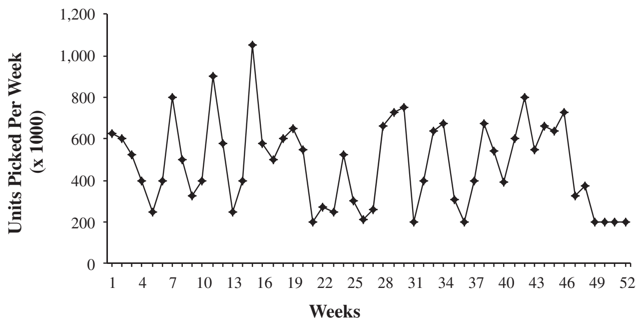

Fig. 1. Weekly variation in the units picked at the warehouse of the US-based apparel supply chain.

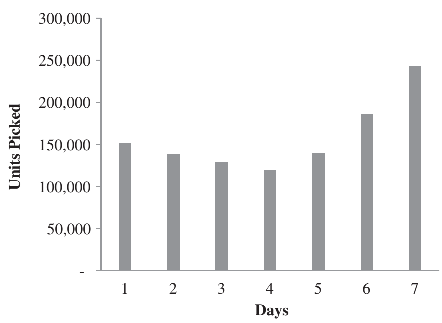

Fig. 2. Variation in the units picked at a warehouse of a *Fortune* 100 US grocery distributor.

the warehouse manager to scramble for resources during peak times and experience resource under-utilization during drought times. Fig. 1 shows the number of units picked per week at the company's warehouse in the year 2011, where the weekly variation in the workload ranges from nearly 42% to 220% of annual average (i.e. the weekly workload varied between 58% below and 120% above the average). Data from another of our industry partners, a Fortune 100 grocery distributor, during August 29–September 4 of 2011, indicated that the weekly workload varied between 76% and 153% of the annual average (i.e. the weekly workload varied between 24% below and 53% above the average) at one of their US warehouses (see Fig. 2).

The key point here is that such workload imbalances create substantial operational inefficiencies at the warehouse and can cost a company millions of dollars annually. From a warehouse operations perspective, a relatively balanced workload across all time-periods is preferred because it leads to (i) easier worker management and scheduling, (ii) reduced need for overtime hours and/or temporary workers, and (iii) effective utilization of technological resources leading to increased worker productivity.

The observed inefficiencies at the warehouse of our industry partners beg the following question: how would a supply chain benefit if it proactively accounted for warehousing decisions at the tactical planning phase, instead of reacting passively every day? This question motivated us to introduce the warehousing-inventory-transportation problem (WITP) to the supply chain literature. The WITP integrates decisions regarding warehouse, inventory, and transportation, and identifies an optimal distribution strategy for a multi-product and multi-period supply chain such that the total distribution chain cost is minimized.

The remainder of the paper is organized as follows. We first summarize relevant literature in Section 2 and then introduce a nonlinear integer programming model for the WITP in Section 3. In Section 4 optimal solutions generated by the linearized version of the WITP model are compared to solutions generated by a sequential approach observed in the industry. In Section 5 we provide details of a heuristic designed to solve industry-sized problem instances (e.g., 500 stores and 1000 products). Finally, in Section 6 we present managerial insights based on our experiments and sensitivity analyses and discuss future work.

2. Background literature

In recent years, researchers in the field of distribution planning have given significant attention to the integration of transportation and inventory decisions. The objective is to balance inventory and transportation costs. A well-studied problem is the inventory-routing problem (IRP), which refers to developing a repeatable distribution strategy that minimizes transportation costs and the number of stock-outs. Both deterministic and stochastic versions of IRP have been studied (Campbell, Clark, Kleywegt, & Savelsberg, 1998; Kleywegt, Nori, & Savelsbergh, 2004; Lin & Chen, 2008; Zhao, Chen, & Zang, 2008). Other approaches to integrating inventory and transportation decisions have also been explored; e.g., Parthanadee and Logendran (2006) and Çetinkaya, Tekin, and Lee (2008).

Abdelmaguid and Dessouky (2006) introduce the integrated inventory-distribution problem (IDP) for multi-period systems considering both inventory and transportation costs, and allowing for backlogging. Lei, Liu, Ruszczynski, and Park (2006) consider the production-inventory-distribution-routing problem (PIDRP), where the focus is on coordinating production and transportation schedules between vendors and customers. Bard and Nananukul (2008) solve a one-plant, multi-customer PIDRP with the assumption of single-mode transportation. Research on the integration of inventory and warehouse location decisions involves identifying an optimal location for the warehouse while minimizing system-wide transportation and inventory costs (Daskin, Coullard, & Shen, 2002; Ozsen, Daskin, & Coullard, 2009; Shen, Coullard, & Daskin, 2003; Üster, Keskin, & Çetinkaya, 2008).

Literature on warehousing is massive, focusing especially on location, design, and operation. Numerous models have been developed to assist in various aspects of warehouse design; e.g., sizing (Goh, Ou, & Teo, 2001; Heragu, Du, Mantel, & Schuur, 2005; Ng, Cheng, Kotov, & Kovalyov, 2009), aisle-layout (Gue & Meller, 2009), and operational aspects (Parikh & Meller, 2010a; Ratliff & Rosenthal, 1983). An area of special focus in warehousing is order picking, which accounts for around 50% (Tompkins et al., 2010). Worker congestion during order picking has been identified as a key factor that causes decreased warehouse productivity and increased costs (Gue, Meller, & Skufca, 2006; Parikh & Meller, 2009, 2010b).

Note that the literature on supply chain planning has focused on integrating inventory and transportation decisions. Warehouses, in the context of supply chain planning, have almost exclusively been treated as nodes with known capacity. To the authors' knowledge, no research exists that evaluates the impact of executing distribution plans on warehouse operations, notably through the variation in warehouse workload. Additionally, warehouse design decisions (e.g., layout, workforce, and technology) and operational impacts (e.g., worker congestion) have a significant bearing on throughput and cost. A fundamental understanding of the implications of warehouse design and operations on inventory and transportation decisions is lacking.

This paper addresses these gaps in the academic literature and concerns expressed by the authors' industry partners by introducing the warehouse-inventory-transportation problem (WITP). The decisions addressed by WITP are compared and summarized in Table 1.