Transportation Research Part E 118 (2018) 240–257

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

Dynamic shipments of inventories in shared warehouse and transportation networks

G. Van der Heide*, P. Buijs, K.J. Roodbergen, I.F.A. Vis

University of Groningen, P.O. Box 800, 9700 AV Groningen, The Netherlands

ARTICLE INFO

Keywords:
Shared warehouse and transportation network
Dynamic shipments
Network comparisons
Inventory
Markov decision process

ABSTRACT

In shared warehouse and transportation networks, dynamic shipments of inventories are carried out based on up-to-date inventory information. This paper studies the effect of network structures on optimal decision-making. We propose a discrete time modeling framework with stochastic demand, capturing a wide variety of network structures. Using Markov decision processes, we obtain optimal order and dynamic shipment decisions for small networks. We compare optimal solutions of different four-node network structures. Results indicate product characteristics significantly influence the effectiveness of network structures. Surprisingly, two-echelon networks are occasionally costlier than any other network. Moreover, dynamic shipments yield considerable gains over static shipments.

1. Introduction and literature review

In recent years, on-demand warehousing marketplaces, such as FLEXE and Stockspots, have been unlocking unused space in hundreds of warehouses throughout the United States and Europe. Companies can use these marketplaces to quickly rent available pallet spaces anywhere in a network of warehouses when needed. At the same time, companies with excess warehouse space can earn some additional revenue. By using networks of shared warehouses, companies avoid the fixed costs that typically come with operating or leasing a warehouse, enabling them to store inventories closer to their end-consumers. On top of that, modern information and communication technologies, such as the Internet of Things, enable real-time tracking of (in-transit) inventories. A product's end-location can be adjusted, possibly even during transportation, enabling dynamic shipments of products between warehouses based on the latest available information. Together, these trends have the potential to reshape the way future transportation and inventory control will be organized.

Inspired by these recent advances, we study the potential benefits of utilizing dynamic shipments in networks of shared warehouses. We will refer to such networks as Shared Warehouse and Transportation Networks (SWTN). In SWTNs, a company may push its products strategically into the network and relocate those products to where they are most needed on a just-in-time basis, providing significant flexibility in dealing with inventory imbalances. Trucks can periodically transport products between connected warehouses in the network. Upon arrival at a warehouse, products can be transported to another connected warehouse in a next period. Usually, not all pairs of warehouses in SWTNs are directly connected. A product may thus need to travel through multiple warehouses to reach its end-location.

As SWTNs may differ vastly in structure, this paper focuses on generating insights into the effects of different network structures

* Corresponding author.
E-mail addresses: g.van.der.heide@rug.nl (G. Van der Heide), p.buijs@rug.nl (P. Buijs), k.j.roodbergen@rug.nl (K.J. Roodbergen), i.f.a.vis@rug.nl (I.F.A. Vis).

https://doi.org/10.1016/j.tre.2018.07.012
Received 21 February 2018; Received in revised form 30 July 2018; Accepted 31 July 2018
1366-5545/

on optimal decision-making for ordering and shipping inventory. In order to achieve this, we first propose a discrete time modeling framework capable of capturing a large variety of different network structures. We then apply that framework to compute optimal order and shipment decisions for several small-sized SWTNs using Markov decision processes (MDPs). The optimal solutions for SWTNs with different structures are compared through several numerical experiments, taking into account the effect of product characteristics such as cost parameters, stock-out behavior of customers, and variance of demand. These numerical experiments provide various scientific and managerial insights for designing effective SWTNs and the added value of dynamic shipments.

In SWTNs, transportation and inventory decisions are fully integrated. Therefore, in the remainder of this introduction, we discuss related contributions in both transportation and inventory research. The emphasis in our review of the literature is on how existing research incorporates the underlying network structure. To the best of our knowledge, we are the first to consider combined transportation and inventory control in SWTNs and we are the first to analyze the effect of network structure on optimal decision-making in such networks.

In inventory research, it is common to first select a specific network structure and then determine (near-) optimal inventory policies for that specific structure depending on, among others, assumptions for stock-out behavior, cost parameters, and demand distributions. This approach is reasonable when the network structure is fixed due to geographical or organizational reasons, as is the case in most warehouse and transportation networks that are dedicated to one or a few companies. Two-echelon networks are most frequently studied (Zhao et al., 2010; Madadi et al., 2010). Moreover, networks are typically assumed to be arborescent, implying a unique path exists from the source node to each end-node. This considerably simplifies analysis, even though it has been argued that arborescent networks are not always realistic in practice (Cattani et al., 2011). An important contribution of our paper, therefore, is the introduction of a modeling framework capable of capturing a wide variety of network structures, including non-arborescent networks. Our framework is inspired by the work of Karmarkar (1981), with the difference that we include positive lead times, as travel times are not negligible in SWTNs, and that we compare different network structures.

Our paper aims to address the lack of in-depth comparisons between different network structures in the literature. Only a small number of authors has made such comparisons, i.e., Muckstadt and Thomas (1980) compare single- and two-echelon policies and Özdemir et al. (2006) compare networks with different transshipment locations. Through our comparisons of small-sized networks, we generate understanding of effective decision-making in a much wider variety of network structures than considered before.

Our modeling framework includes multi-echelon models, for which optimal solutions can only be derived analytically in special cases (see, e.g., De Kok et al., 2018). Moreover, effective heuristics typically rely on exploiting the arborescent structure (Cattani et al., 2011). With this in mind, it is beyond the scope of our paper to develop exact or heuristic solution methodologies for general network structures. However, insights from our comparisons may assist in developing heuristics for general network structures in future research.

Several problems in transportation research feature adaptive decision-making based on stochastic information. For example, in dynamic vehicle routing problems routes can be adapted in real-time or periodically when stochastic demands arrive (Pillac et al., 2013; Ritzinger et al., 2016). Strategically placing goods in dynamically changing networks has been the subject of several studies in the domain of humanitarian logistics (e.g., Özdamar et al., 2004; Rennemo et al., 2014; Ahmadi et al., 2015; Alem et al., 2016), where relief goods must be transported through a network whose edges and nodes can become unavailable due to disasters. In SWTNs, the main issue is also strategic placement and transportation of products in the network in anticipation of and in response to random events. Prior studies in that regard have addressed problems with limited horizons, whereas we are interested in analyzing inventory and transportation policies for the long-run.

The integration of transportation and inventory decisions is mainly studied in regards to inventory-routing (Coelho et al., 2013) and vendor-managed inventory problems (Govindan, 2013; Marquès et al., 2010). In vendor-managed inventory (VMI), a vendor has the responsibility to manage its inventory at one or more retailers (Dong and Xu, 2002; Disney et al., 2003). Accordingly, a two-echelon network structure is natural when studying VMI (Yao and Dresner, 2008; Chen et al., 2010; Gürler et al., 2014). Typically, inventory at retailers is controlled through parametric policies such as periodic review order-up-to policies (Yao and Dresner, 2008). After the parameters of these policies are set heuristically, inventory-routing problems can be solved to obtain effective routes (Coelho et al., 2013). Such inventory-routing problems are classical in the sense that typically vehicles start from and return at the same warehouse, visiting several customers on a route. In SWTNs, the main concern is not routing vehicles, but routing products over available connections. The network structure in SWTNs can, therefore, differ substantially from a two-echelon structure. Moreover, the possibility to store products at and transport products between warehouses based on newly arriving inventory information enables new dynamic VMI strategies. In our numerical experiments, we consider a company responsible for inventory control at multiple warehouses, which can be regarded as the first application of VMI in SWTNs.

SWTNs are also a fundamental element of the Physical Internet initiative (Montreuil, 2011), which is gaining attention from researchers and practitioners (Treiblmaier et al., 2016; Pan et al., 2017; Sternberg and Norrman, 2017). The Physical Internet initiative relies on the analogy with the digital internet to inspire innovation in logistics. In the digital internet, information packages are sent automatically from source to destination through a network of hubs with the use of routing protocols. Similarly, in the Physical Internet (PI), a company simply specifies a destination for a physical product, and then trusts the system to arrange its transportation and storage. Products potentially travel through multiple, "open" warehouses and can be combined – and re-combined – with other products at every warehouse along the way. This may help to address possible mismatches between inventory fitting in a truckload and the inventory required at an end-location, either giving rise to excess inventories (when shipping full truckloads) or poor vehicle utilization (when carrying out small-sized shipments). Early studies indicate that PI can increase consolidation of transport when products of multiple companies travel in the same direction. As a result, it enables considerable improvements in truck utilization and reductions in CO_2 emissions (Sarraj et al., 2014a). Accordingly, the European Commission strives to realize PI by