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A non-myopic dynamic inventory routing and pricing problem

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ABSTRACT

A new framework for the design of a dynamic non-myopic inventory and delivery network between suppliers and retailers under the assumption of elastic demand—one that simultaneously incorporates inventory, routing, and pricing—is proposed. The developed queuing approximation method is based on optimal tolling of queues. We propose a dynamic approach for a supplier who has to deliver products to a number of retailers while maximizing social welfare through dynamic pricing that accounts for customer waiting times, inventory holding, lost-sales costs, and delivery costs. The proposed non-myopic model increases the social welfare by up to 17% compared to the marginal pricing case.

1. Introduction

Combining inventory management and vehicle routing problems yields a complex optimization problem in logistics called the inventory routing problem. To gain a competitive advantage, suppliers can reduce the total cost of their operations by optimizing vehicle routing and inventory decisions simultaneously instead of optimizing them separately. To make these decisions jointly, what is needed is a smart inventory routing strategy that combines inventory holding, replenishment, and lost-sales costs in the context of a flexible dispatch policy. Under such a strategy, the supplier would work with retailers to monitor inventory levels, and decide when and how much inventory to replenish for each retailer. This system would have several advantages for suppliers, as it would allow for a more uniform and effective utilization of production resources, which would in turn lead to reductions in inventory holding and production costs. Suppliers would be able to achieve additional savings in the form of reduced transportation costs by managing demand, identifying optimal routes, and increasing the use of full-truckload shipments.

The pricing decision affects the demand decision, which in turn affects the inventory and routing decisions, all of which should be incorporated simultaneously into a flexible inventory routing problem to achieve the objective of maximal social welfare in the supply chain under the assumption of elastic demand. The combination of inventory management, vehicle routing and pricing strategies yields a complex logistics optimization problem called the inventory routing and pricing problem (IRPP). To consider the vendor-managed inventory (VMI) replenishment benefits for retailers, the pricing decision has to account for inventory, routing, and pricing simultaneously. According to a survey of the literature, no previous work has addressed the IRPP (Liu and Chen, 2011), but some researchers (Nachiappan and Jawahar, 2007; Lau and Lau, 2003) have determined prices and demands by using a known (linear) demand function based on the maximal profit criterion. One potential innovation to the IRPP is the concept of flexible inventory routing services, which they define as real-time services that transport goods without a fixed route and/or schedule designed.

The growth of population and demand in cities has led to an alarming rise in traffic congestion and air pollution levels, with the attendant environmental and health concerns, compelling more and more metropolitan areas to use smart systems for the transport of

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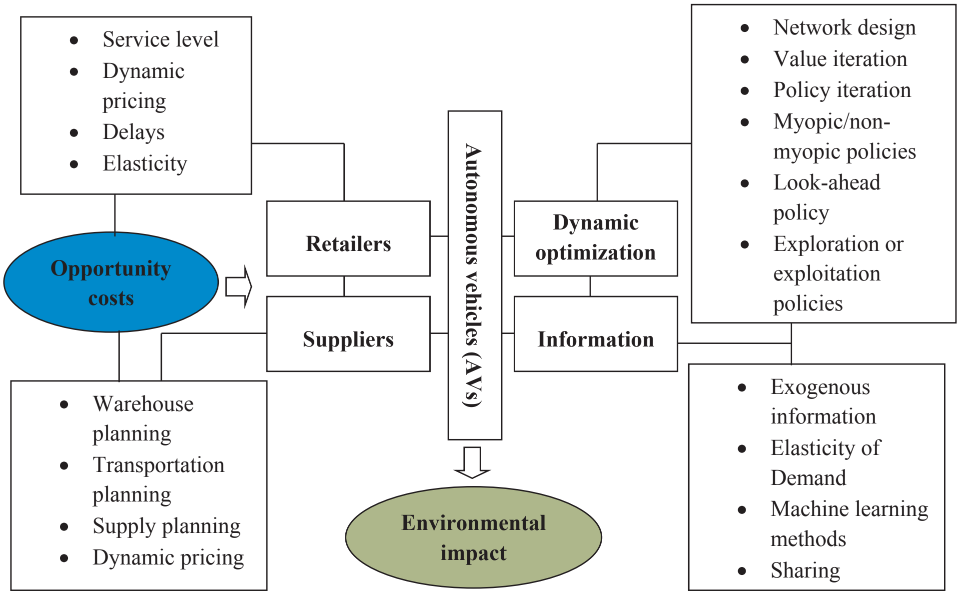

Fig. 1. Smart inventory routing/pricing problem and environmental impact.

freight and passengers. Autonomous vehicles (AVs), for instance, move passengers or goods without human intervention. AVs are potentially disruptive, both socially and technologically, with claimed benefits comprising increased safety, better road utilization, energy savings, and driver productivity. The recent emergence and rapid expansion of self-driving trucks provide not only direct competition for traditional services, but also opportunities for revolutionizing the high cost, low safety, and high environmental impacts of conventional delivery methods (Greenblatt and Shaheen, 2015). AVs are extremely sophisticated systems that require high-performance computational hardware, state-of-the-art online models, decision-making algorithms, and real-time information. Our methodology could be of great use in the routing of self-driving trucks and other AVs within different delivery systems.

Real-time information introduces a new dimension to decision-making in dynamic models. Online models involve an iterated process: making decisions, accessing information, then making more decisions, accessing more information, and so on. A dynamic decision process with discrete time intervals can be modeled using a Bellman equation (Powell, 2011), as follows:

$$V_t(R_t) = \min_{x_t}(C_t(R_t,x_t) + \gamma \mathrm{E}[V_{t+1}(R_{t+1})|(R_t,x_t)]), \tag{1}$$

where V_t is the value of the optimal dynamic policy, C_t is the immediate payoff of the decision x_t under state R_t, and γ is a discount factor; R_t is also typically driven by information on exogenous stochastic variables. In this process, a queue delay is used to approximate the conditional expected future cost term $E[V_{t+1}(R_{t+1})|(R_t,x_t)]$ in a type of approximate dynamic programming. In a large-scale inventory routing network setting, the amount of data generated from the network is massive, rendering computation of the one-step transition matrix difficult or impossible. However, the approach we propose is not limited to only a single time-step look-ahead, and instead approximates the expected average future value over an infinite horizon.

Fig. 1 shows a framework of methods and data sources needed to ensure a viable "smart" inventory routing and pricing system. For example, such a smart system can be created through the implementation of technologies, dynamic models, and real-time information systems. Information-updating mechanisms are essential in a smart IRPP, because inputs are continually changing. Policies that do not anticipate future requests are referred to as myopic policies, while policies that anticipate unknown future requests are called non-myopic policies. The process of machine learning in approximate dynamic models consists of "exploring" a state for decision-making, or of "exploiting" current calculations of downstream values to make what we think is the best possible decision (Sayarshad and Chow, 2016; Chow and Sayarshad, 2015). Combining a non-myopic inventory routing system and AVs can provide such potential benefits as environmental improvements, increased safety, improved supplier productivity and service levels, more efficient road usage, and energy savings. The demand and inventory are linked together under look-ahead policies that predict and anticipate future states, thereby resulting in improved economy and information sharing, since changes in future profits or opportunity costs are associated with serving more retailers.

The contributions of this work can be summarized as follows:

- We develop a non-myopic inventory routing problem under infinite-horizon look-ahead that maximizes social welfare with respect to delays experienced by retailers and inventory costs. The model provides a one-to-one relationship between prices and optimal arrival rates.
- We provide an optimal price point that considers the socially efficient price, by also accounting for customer delays—as opposed to the standard monopoly pricing mechanisms, which are used in pursuit of the revenue-maximizing price. Moreover, we show