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Optimal allocation of limited and random network resources to discrete stochastic demands for standardized cargo transportation networks

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ABSTRACT

We consider the resource allocation problem with discrete random demands and discrete random resource capacities for standardized cargo transportation networks, in which a freight operator needs to determine the integral quantity of booking requests to be accepted for each product to maximize the expected profit. We formulate the problem as a stochastic integer programming model and provide theoretical results that completely characterize the optimal solution to the stochastic model under a special case. We present a progressive augmentation algorithm and a sampling based method for solving the stochastic model under a general case. We also offer numerical experiments to test the two methods and shed light on their performances.

1. Introduction

We consider a *freight operator* who operates a standardized cargo (e.g., 20 ft containers) transportation network and offers periodically repeated services of cargo transport to shippers in a spot market. The operator sells a set, $\mathcal{N} := \{1, 2, \ldots, n\}$, of products to the market, where each *product* is defined as the transport service specified with a particular combination of origin-destination (O–D) pair, itinerary, and price. Each product consumes a subset of a collection, $\mathcal{M} := \{1, 2, \ldots, m\}$, of resources, where a *resource* is interpreted as a type of standardized cargo slots over a leg on the itinerary, such as 20 ft container, 40 ft container, reefers (i.e., refrigerated containers for the transport of temperature sensitive cargo such as frozen meat), or standard pallet slots.

In particular, we restrict our attention on standardize cargo transportation, in which products are sold in terms of slots for standard cargo units (e.g., the slots for 20 ft/40 ft containers on container ships) and cargo is accepted if there still exist available slots, as is discussed in Zurheide and Fischer (2015) and Gorman (2010). This is different from air cargo transportation (Amaruchkul et al., 2007), in which cargo acceptance is often constrained in two dimensions — weight and volume.

Network effects. There may exist interdependence between products. Multiple products may share a common resource, causing that selling one of the products reduces the inventories of all other products that use the same resource. This phenomenon is referred to as the network effects. We use a *resource-product incidence matrix* $\mathbf{A} = [a_{i,j}]_{m\times n} \in \mathbb{Z}_+^{m\times n}$, where $\mathbb{Z}_+ = \mathbb{N} \cup \{0\}$, to model the network effects, in which each entry $a_{i,j}$ represents the units of resource $i \in \mathcal{M}$ used by product

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$j \in \mathcal{N}$. When **A** is diagonal, there exist one-to-one correspondences between resources and products, i.e., each product uses only one resource and each resource is only consumed by one product. The network with a diagonal **A** corresponds to the single-leg market with parallel services (Moussawi-Haidar, 2014).

Network resource allocation. A shipper requests a booking of the service from the freight operator to deliver one or a group of shipments from a specific origin to a specific destination. In response to the request, the freight operator sells a product to the shipper. The freight operator makes revenue by providing resources to shippers. With limited resources, it is of central interest to the freight operator to make a good control of bookings to optimize the use of her resources.

We are interested in the *stochastic network resource allocation problem*, in which the freight operator attempts to predetermine the quantity of booking requests to be accepted for each product during the selling horizon for a specific service period, accounting for network effects and the operations practice that shippers' demands (booking requests) come at random and the freight operator's resource capacities are uncertain. In particular, we consider that the demands and resource capacities are *discrete* random quantities, in order to be consistent with practical operations, under which the quantity of booking requests received for each product is an integer and the amount of each resource owned by the freight operator is also a whole number.

Uncertain capacity. While it has become one of the conventions to treat customers' demands in a spot market as random, there is no sufficient attention paid on the uncertainties in service providers' capacities. We consider that there is for each resource a maximum possible capacity that the freight operator can provide. The maximum capacity can be thought of as the fixed *planned/designed* capacity. However, the freight operator may not always have the full planned capacity realized during service operations. For instance, an intermodal service provider has well planned truck services for transporting a fixed capacity of 20 boxes from the port of Los Angeles to Memphis; the realized capacity just drops down to zero because of the occurrence of the Los Angeles port strike (International Business Times, 2015) on the departure day. We refer to the realized actual capacity at the time of service as the *working capacity* or *capacity* for convenience. There exist cases where the working capacities of infrastructures and vehicles experience unexpected disruptions and become uncertain in nature.

The uncertainties in the working capacities could stem from various sources, such as (i) the acts of nature such as hurricanes, floods, snow storms, and earthquakes, (ii) the acts of humans such as labor strikes, accidents, and terror attacks, and (iii) unexpected plan changes or randomness in supply during service operations, such as random yields (Okyay et al., 2014; Yano and Lee, 1995). In fact, random capacity has grabbed attention of researchers in transportation: Chen et al. (2002) discussed random link degradation, Sumalee and Kurauchi (2006) analyzed network capacities after a disaster, and Lo and Tung (2003) focused on travel time reliabilities with random link capacities. In particular, Chen and Miller-Hooks (2012) argued that arc capacities in intermodal freight transport depend on disruption-causing events and therefore uncertain. They further represented arc capacities as random variables.

Thus, to reflect the operational reality, we consider that each resource's capacity is random. Meanwhile, we interpret each resource's designed capacity as an upper bound that represents the maximum quantity of the resource that the freight operator can afford to provide.

Offload and spoilage. However, since demands and capacities are both random, there could exist *offload*, in which the resources required to accommodate the accepted requests exceed the realized resource capacities, or *spoilage*, in which the realized resource capacities are more than enough for the accepted product requests. As a result, the freight operator will be penalized against the shortage of resources if offload happens, and on the other hand, if there are leftover resources, the freight operator might charter them out to other freight operators for getting some salvage value. The profit thus includes the sales revenue and salvage value less the shortage costs.

Objective. The objective of this work is to determine the optimal resource allocation decision that prescribes the optimal integer quantity of booking requests that the freight operator pre-commits to accept for each product (i.e., the booking limit) during the booking horizon to maximize the expected profit, accounting for discrete random demands and discrete random resource capacities.

1.1. Challenges, our solutions, and positioning

To achieve the objective, we formulate the stochastic resource allocation problem as a stochastic integer programming model, called the STOC model, that incorporates three important aspects of the problem: random resource capacities, stochastic product demands, and network effects. As far as we know, there exist no published results on the network resource allocation problem with uncertain resource capacities. As one of the innovations of this work, we concurrently consider *discrete* random demands, *discrete* random resource capacities, and *integral* booking limits to reflect the operational reality, which has not been addressed in the previous literature but further complicates the problem: the resulting objective function of the STOC model is non-differentiable and we have to deal with an NP-hard integer program.

One of the classical methods to solve the resource allocation problem with discrete random demands is to transform stochastic models to tractable linear programs (c.f. Williamson (1992) and Talluri and van Ryzin (2004, pp. 95-96)). The method exploits an important model structure that the objective function is separable in decision variables. Unfortunately, the method cannot be applied to solve the STOC model, in which the objective function involves the resource-product incidence matrix and random capacities, making it no longer separable in decision variables. Thus, there is a need to develop a new solution method to solve the STOC model. We study the STOC model under two different cases and provide a dedicated treatment for each of the cases.