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Supply capacity acquisition and allocation with uncertain customer demands

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ABSTRACT

We study a class of capacity acquisition and assignment problems with stochastic customer demands often found in operations planning contexts. In this setting, a supplier utilizes a set of distinct facilities to satisfy the demands of different customers or markets. Our model simultaneously assigns customers to each facility and determines the best capacity level to operate or install at each facility. We propose a branch-and-price solution approach for this new class of stochastic assignment and capacity planning problems. For problem instances in which capacity levels must fall between some pre-specified limits, we offer a tailored solution approach that reduces solution time by nearly 80% over an alternative approach using a combination of commercial nonlinear optimization solvers. We have also developed a heuristic solution approach that consistently provides optimal or near-optimal solutions, where solutions within 0.01% of optimality are found on average without requiring a nonlinear optimization solver.
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1. Introduction

A common problem faced by physical goods suppliers is how to best set production capacity levels and allocate this capacity to customer demands. Many large firms operate using several facilities that are usually strategically located across a region. When assigning customers to these facilities, we often find in practice that the demands of each individual customer or market are fully assigned to a single source facility. This restriction is used in order to reduce planning coordination complexity and is often preferred by customers who wish to have a single, consistent point of contact for supply. Therefore, the problems we consider will incorporate this practice of assigning each customer's demand to a unique source facility. In constructing such a supply network for customers, the supplier must determine which customers will be assigned to each source facility as well as the capacity level at each facility.

For the contexts we consider, these capacity acquisition and customer assignment decisions are fixed in the short run, and must be determined prior to actual customer demand realizations. We therefore face a combined capacity acquisition and assignment problem with uncertain customer demands. The capacity and assignment decisions are effectively made in the first stage of a two-stage stochastic programming problem with simple recourse, where the actual customer demand realizations determine the resulting capacity utilization and capacity overflow costs. Our goal is to set capacity levels and determine assignments in the network in order to minimize expected capacity acquisition, utilization, and capacity overflow costs. We use the term *capacity* generically, as this capacity may in certain contexts refer to the capacity that inventory provides in satisfying customer demands.

Our class of stochastic assignment problems has several applications within operations planning contexts, and we next discuss three such problem settings. The first setting considers a product with a single-selling season, as in the classical newsvendor model, where the facility capacity corresponds to the aggregate inventory acquired from an outside supplier with a long supply lead time. Each regional distribution center in a network of facilities is therefore allocated a stock level (the capacity) and uncertain customer (or market) demands for the product are assigned to each facility. For example, all customers residing in a certain subset of zip codes may be assigned to a given distribution center for product distribution. Our goal is to determine stock levels and customer assignments for each facility in order to minimize expected procurement, holding, and shortage costs across all facilities. As we later note, our model also extends to periodic-review, infinite-horizon distribution planning problems when customer demands are stationary and inventory shortages result in backorders. In such settings, because customers often prefer a consistent single-point-of-contact or source of supply, assignments are often fixed in the short run and cannot be dynamically varied after demand realization in each period.

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The second application we might consider is in setting make-to-order manufacturing capacity at production facilities who serve the needs of multiple customers. In this context, each customer assigned to a facility requires utilizing some of the manufacturer's production capacity in each period. For example, it is not an uncommon practice in electronics contract manufacturing for the manufacturer to dedicate a production line at a particular facility to certain high-value customers. The amount of capacity required by each customer every week is a stationary random variable, and the aggregate customer demand assigned to a facility (or production line), along with the facility's capacity level, determine the weekly capacity utilization and overflow costs. As in the infinite-horizon distribution planning problem case, customers often prefer to receive their supply from a single source on a consistent basis, which precludes dynamically varying supply assignments. Our goal is to minimize manufacturing capacity acquisition plus expected capacity utilization and overflow costs across the network of facilities.

A third potential application area is in the distribution of goods from warehouses to retail customers via trucks. In an ongoing distribution context, each regional distribution center is allocated an aggregate truck delivery capacity that is used for weekly scheduled deliveries to retail customers. Retail customers, whose demands from week to week are stochastic (but stationary) are allocated to upstream distribution facilities. The aggregate demands of customers assigned to a facility in each week, along with the truck capacity at the facility, determine the expected truck utilization costs, as well as the associated demand overflow costs. We wish to allocate truck capacity levels to each facility while assigning retail customers to facilities in order to minimize truck capacity plus expected utilization and overflow costs.

For analytical tractability, our modeling and solution approach rely on two important assumptions. First, we assume that facilities within the network cannot share capacity (in an inventory stocking and distribution context, this implies that transshipments are not permitted). Second, we assume that when a facility's capacity is exhausted by customer demands in a period, either an outside local emergency source is available to satisfy any overflow, or customers are willing to wait until a later period for demand satisfaction (in the distribution context, this implies that customers will accept backordering). This assumption is not unreasonable in a number of contexts, particularly in light of the many contract manufacturers, third-party logistics providers, and quick response manufacturers that exist today. Taken together, these assumptions imply that it is cheaper for a facility to either utilize the local emergency outside source or delay demand satisfaction than it is to draw from excess capacity available at other facilities in the supplier's network. These assumptions not only lead to tractable solution methods for a broad set of problems, but can also provide an effective set of approximate models and capacity planning tools for contexts where the assumptions may be slightly violated, i.e., where the economics or management preferences require a high level of product availability such that transshipments and capacity overflows at facilities occur infrequently. Moreover, although combined capacity and customer assignment planning problems are not always solved simultaneously in practice, an integrated model that concurrently determines capacity levels and customer assignments can suggest the most efficient match between capacity and customer demand. The model's solution can therefore serve as a benchmark to identify inefficient capacity levels and/or customer assignments in practice.

The application of stochastic programming models to operations management problems has been widely studied, particularly in recent years. For references to books and survey articles on the subject, see Birge and Louveaux (1997), Prékopa (1995), Schultz et al. (1996) and Sen and Higle (1999). Capacity acquisition and allocation problems under uncertainty have been studied for many years, using two-stage stochastic programming with recourse (see, e.g., Mine et al., 1983; Berman et al., 1994; Eppen et al., 1989; Fine and Freund, 1990; Swaminathan, 2000). Eppen et al. (1989) provide such a model based on actual data from the automotive industry, where they set production facility capacities using a model with scenario-based demand data (where demand levels include pessimistic, standard, and optimistic scenarios). Fine and Freund (1990) develop a model that determines levels of both product-specific and flexible capacity to be allocated to the anticipated demand for each of its product families. Swaminathan (2000) considers investment in capacity levels of wafer fabrication tools that can process demand for wafers, where wafer fabrication processing times depend on the tool to which the wafer type is assigned. Prior work in this research stream allows splitting the processing requirements of a task among multiple resources, which implies that the capacity allocation problem in the second stage is a linear program. In contrast, we require integral customer-to-facility assignments, which leads to a more difficult class of generalized assignment problems in the second stage.

Another rich stream of literature extends from Fine and Freund (1990). Investing in flexible resource capacities has been studied by Bish and Hong (2006), Bish and Wang (2004), Chod and Rudi (2005), Netessine et al. (2002) and Van Mieghem (1998), to name a few. Bish and Wang (2004) consider a two-product, price-setting firm and study the structure of the firm's optimal resource investment decision in the presence of a fully flexible resource option. In a similar manner to Netessine et al. (2002), they account for demand correlation. Their work also extends the results of Van Mieghem (1998), who considers a similar setting but under exogenously determined prices. While much of the literature considers a fully flexible resource structure, where the flexible resource can produce all products, Bish and Hong (2006) examine the concept of downward resource flexibility, in which resources that can satisfy higher-level products can also be used to satisfy the lower level products, but not vice versa.

Deterministic versions of the classical assignment problem and the generalized assignment problem (GAP) have also been well researched (see Kennington and Wang (1991) and Cattrysse and Wassenhove (1992), respectively, for reviews of each problem, as well as recent GAP extensions studied in Freling et al. (2003) and Huang et al. (2005)). Only recently has the stochastic version of the GAP received increased attention (see Albareda-Sambola et al., 2006; Spoerl and Wood, 2003; Toktas et al., 2006). Our work differs from past research in that nearly all of the past work on stochastic assignment problems has assumed pre-determined facility capacities.

None of the papers discussed thus far considers a combined customer-to-facility assignment and capacity-installation problem as we address in this paper. Ahmed and Garcia (2004) present a dynamic capacity acquisition and demand assignment problem that is the most closely related to our work. As in our paper, capacity acquisition and assignments are decision variables, and they determine fixed capacity levels within which the firm will operate. They also require all demand-to-facility assignments to be integer (single sourcing), whereas past work cited on capacity expansion and allocation allowed fractional assignments. In contrast to our work, however, they allow demand assignments to be made after actual demands are realized in each period, as might occur in a make-to-order context. We require customer-to-facility assignments to be first-stage decisions that cannot be altered in the short run, as would be the case when customers require short delivery lead times subsequent to order placement. Our approach also applies to situations in which customers place orders periodically to supply facilities subsequent to capacity installation, when the sequence of each customer's demands corresponds to a stationary

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