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Part commonality effects on integrated network design and inventory models for low-demand service parts logistics systems

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ABSTRACT

Low demand logistics systems with response time based service levels such as service parts supply chains exhibit strong interaction between network design and part stocking decisions motivating integrated models making such decisions simultaneously. Extending the earlier models of single product, single part systems, we formulate a multi-product service parts supply chain design problem with part commonality. In particular, our model captures (1) multiple multi-part products with part commonality across products, (2) system-wide, product-specific, time-based service requirements, and (3) stochastic demand satisfied by facilities operating with one-for-one replenishment inventory policy. We then linearize this naturally non-linear integer program via approximation of fill rate function and introduction of new variables to handle quadratic terms in the constraints. We finally conduct a numerical study to quantify the effects of part commonality on network design and inventory decisions and costs using this linear integer reformulation. Our results show that dedicated parts (ignoring commonality) can lead to significantly suboptimal decisions, not only on stock levels but also on network design (location and demand allocation) decisions. Furthermore, our tests with relatively larger networks show that considering part commonality, even in a sequential approach of deciding network design first and part stocking decisions next, significantly improves the total costs of network design and inventory.

1. Introduction

Capital goods manufacturers typically extend their involvement in the product lifecycle beyond initial sales through service contracts, spare parts and repair services. They see the potential for additional revenue in post-sales services and in repeat sales due to increased customer loyalty. Customers demand responsive post-sales services to keep such mission-critical goods fully utilized during their useful life (usually anywhere from 5 to 20 years). Medical equipment, business machines, heavy equipment, aircraft, and high technology products can be listed as examples within this category. Providing responsive and high quality long-term customer service is a costly undertaking for the manufacturers. A manufacturer typically has to employ a far reaching service network to quickly satisfy demands for parts and service coming from their installed customer base dispersed geographically. Deciding where to position inventory, how much to stock, and how to allocate customer demands to service locations, are all critical to meeting customer requirements while keeping costs under control.

Previous studies show a strong interaction between network design (positioning stocking locations and allocating demand to these locations) and part stock levels for ultimate optimization of the system-wide performance in service logistics systems (see Candas and Kutanoglu (2007)). Although successful in showing the benefits of explicitly considering inventory in network design, these studies do not consider part commonality, an important aspect of actual service supply chains. Since they focus on simplified settings with single product, single part systems, it is impossible to take part commonality into account. However, most capital goods manufacturers sell and service a variety of large and complex products (machines, equipment, etc.) consisting of many individual parts, taking advantage of common parts both in manufacturing the product and in servicing it after sale. The effect of part commonality on inventory decisions, viewed as a way of variability pooling, is rather well understood, especially in assemble to order systems (see, e.g., Baker (1985); Song and Zhao (2009)). Here, we consider multiple product service parts logistics (SPL) systems and explicitly analyze the effects of part commonality on network design as well as on inventory. To the best of our knowledge, there are no such studies in the general location and network design literature, let alone in the more specialized low demand or service parts logistics research.

To setup the problem with part commonality, we build on our

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existing single product, single part formulations for service parts logistics network design (LND) problem with inventory stocking. The problem is designing a network of part stocking/service facilities, allocating individual customer demands to the located facilities and determining part stock levels to be maintained at these facilities. Demands are for parts that are needed to replace the failed parts in the existing machines/systems (called products in general) already being used at customer sites dispersed geographically.

Product level service requirements (which are derived from the service level agreements between customers and the manufacturer/service provider) spell out a service level to be achieved for all the parts that are used in a product specifying percentage of demand to be satisfied within a service time window for all customer sites. One can view a multi-site customer account (say a retail chain such as Walmart or a hospital network) enters into a contract that stipulates a service level agreement with the service provider: The product in question across all customer sites must be up and running within a certain time window with a certain percentage of the time. This means that from the customer account point of view the most important issue is whether their use of the product under consideration achieves the promised service level, not whether an individual customer site's or an individual part's or an individual facility's service is high. We note that this setup (hence our model and its results) applies to many SPL systems with such concerns, but not all. If that is the case, modifying the model to the easier part-level, facility-level or customer-level service problem is rather straightforward. The main caveat is that the importance of the part commonality issue would be hard or impossible to capture in such disaggregated structures. Finally, as additional justification and consideration for service allocation, we note that many SPL-related studies consider similar aggregate service level constraints. In addition to the reference book on SPL inventory management by Muckstadt (2005) which also covers this issue, we list a few other relevant references here: Cohen et al. (1989); Hopp et al. (1999); Caggiano et al. (2007, 2009); Topan et al. (2017).

Hence, the service levels are defined for each product (as it is used by the multiple customer sites), but the stocking unit is parts. Therefore, we need to make sure that (1) we position the facilities at the right places in the network, and (2) we stock the right parts at the right places so that the part availabilities needed to guarantee product-specific time-based service levels are achieved. As one can achieve a product-specific service through different parts and through different locations, we have a two-dimensional *service allocation* problem within our models, across facilities, and across parts. That is, instead of assuming a fixed and constant part availability (or fill rate) for each part and for each facility, we let the model decide demand allocations and stock levels which eventually considers all potential fill rates across parts and facilities and decides how the overall product-specific service should be allocated to individual parts at individual facilities. This issue leads to a strong interaction between network design and inventory stocking decisions and it is further complicated by part commonalities across products.

This problem setup means that there is a structure (which part goes into which product) that captures the relationship between parts and products and part-level decisions affecting the product level service. The driver behind this is that customers buy products and expect service for their products, not for their individual parts. Specifying a priori part service level or availability to individual parts would greatly simplify the overall problem but would be sub-optimal given that the model in our paper has the full flexibility of allocating product level service to the parts optimally. This way, incorporating the service allocation problem is more comprehensive, more realistic, more interesting and rich, and more challenging which deserves this focused effort to solve. Moreover, we further model part commonality within an integrated location and inventory model for service parts logistics and the structure between the parts and products should be captured explicitly if we are to show the effects of part commonality.

Given the vast amount of literature on inventory related research, even when restricted to service parts, we limit our review to part commonality issues within SPL network design and inventory stocking problem. We refer the reader interested in SPL inventory management research to Sherbrooke (2004) and Muckstadt (2005). There has been an increasing interest in integrated network design and inventory stocking models (also called joint location and inventory models), majority of which are more suitable for high-demand settings taking advantage of the EOQ-type ordering policies or consider more simplified version of safety stocks and/or inventory levels (see, e.g., Erlebacher and Meller (2000); Nozick and Turnquist (2001); Daskin et al. (2002); Shen et al. (2003); Miranda and Garrido (2004)). Few studies focus on low demand settings such as SPL within the integrated framework, e.g., Candas and Kutanoglu (2007) and Jeet et al. (2009), which also provide extensive review of the integrated network design and inventory stocking literature, be it high demand or low demand settings.

Part commonality in general inventory theory, especially as applied to assemble to order systems, is well studied and its explicit consideration is known to reduce stock levels saving inventory costs, due to its variability pooling effects. Collier (1981, 1982); Baker (1985); Baker et al. (1986) and Gerchak et al. (1988) are early studies in this regard. Mirchandani and Mishra (2002) analyze product prioritization (for the use of common parts) and different types of service levels (aggregate or disaggregate) within the part commonality context. More recently, Song and Zhao (2009) study the value of part commonality in an inventory system with positive lead times and identify conditions (e.g., commonality structures) under which part commonality provides inventory cost benefits. We are aware of only one SPL-specific part commonality study by Krannenburg and van Houtum (2007) who focus only on inventory issues for increasing levels of commonality. Here, we take the part commonality in the product structure as given (with multiple product-part structures with varying levels of commonality tested) and investigate its effect not only on inventory but also on network design decisions. We also compare the optimal networks of the new generation part-commonality models with those of the previous models that assume dedicated parts (ignoring part commonality). Our comparison shows that the benefits of exploiting part commonality in network design as wells as inventory stocking can be significant under variety of conditions.

2. Problem statement and modeling

In this section, we first state the problem, then list the assumptions that we make to facilitate the model (Section 2.1). After presenting our model in Section 2.2, we introduce fill rate approximation and linearization (Section 2.3). Since our current multi-product model with part commonality extends the previous models (Candas and Kutanoglu (2007) and Jeet et al. (2009)), we do not repeat the model development in detail (we refer to these papers for detailed model development, especially for modeling service level constraints, and sequential solution approach) but keep the discussion here self contained with minor overlap with these earlier models.

Given a set of customer sites and their demands for replacement parts and product structures (what parts are in what products), we seek to locate a set of facilities selected from a set of candidate facility locations, allocate all demands to the facilities we open, and also determine part stock levels to be maintained at each open facility. The objective is to make these decisions at the minimum joint costs of opening facilities, shipping parts from facilities to customers in need, and stocking inventory, while achieving the target time-based service levels for each multi-part product.