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Sourcing assemble-to-order inventories under supplier risk uncertainty

Yoo Suk Hong [a], Woonghee Tim Huh [b], Changmuk Kang [c,*]

[a] Department of Industrial Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 151-742, South Korea
[b] Sauder School of Business, University of British Columbia, 2053 Main Mall, Vancouver, BC, V6T 1Z2, Canada
[c] Department of Industrial and Information Systems Engineering, Soongsil University, 369 Sangdo-ro, Dongjak-gu, Seoul 156-743, South Korea

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ABSTRACT

In this paper, we consider sourcing and inventory spare-parts decisions in an assemble-to-order setting wherein components are subject to defect risk. Sourcing from dual suppliers diversifies the defect risk and reduces the variability of random defects. Upon careful consideration of assemble-to-order (ATO)-type repair and uncertainty of supplier reliability, we found that dual sourcing minimizes spare-part inventory cost by reducing the shortage cost or enabling storage of lesser amounts of the common resource. This paper identifies the conditions under which dual sourcing is better than sourcing from a single supplier in spite of lost pooling effect, higher procurement cost, and failure to achieve higher reliability.

1. Introduction

Uncertainty surrounding supplier reliability is an important issue in supply chain management. Among the various sources of supply risk, the quality risk of undetected defects causing product failures is the focus of this paper. This risk is distinguished from the yield risk of receiving random portions of orders from suppliers. For manufacturers, product failure incurs significant quality costs in the forms of warranty repairs, recalls, or lost reputation [28], which can in fact be much larger than costs from unreceived orders. As Yim [51] and Kang et al. [23] emphasized, *supplier diversification* is an effective strategy for mitigating this risk, since defects of components are correlated when they are supplied from the same supplier.

In this paper, we quantitatively evaluate the effectiveness of a dual-supplier risk-mitigation strategy in terms of the expected cost of repairing products with defective components. Repair cost is a direct consequence of observed defects. The manufacturer offers warranty repair in the case of individual products, or announces a recall campaign if a significant proportion of products are likely to have the same defect. The more the defects that are observed, the higher the repair cost that is required. We model the repair cost as the repair-service cost combined with the newsvendor inventory cost of stocking repair resources such as spare parts. The stylized assumption of newsvendor inventory is simple, but adequate for revealing the risk-mitigation effect of the diversified sourcing strategy. Also in practice, according to the empirical study of Bacchetti and Saccani [3], companies generally keep safety stock for spare parts.

The repair inventory we consider is distinct from ordinary newsvendor inventories for random spare-part demands in two key aspects. First, the manufacturer does not know the exact probability of defects, but only has a general idea based on supplier reliability. Tomlin [42] noted that manufacturers often do not know the true distribution of supplier uncertainty, even for repetitive manufacturing variations that cause random yields. In this case, the manufacturer can mitigate the risk of procuring from a sole unreliable supplier by employing another supplier who may be reliable. In this paper, the reliability uncertainty is conveniently modeled as a mixed defect-probability and defect-number distribution; a defect randomly occurs according to the defect probability, which is also a random variable following a two-point distribution that has zero or a positive value. Second, the manufacturer needs to stock another inventory of the resource that is commonly required for repairing defective components from any supplier. An example of such common resource would be a repair service capacity or a physical component that is integrated with a defective one. Herein, for the purposes of analytical simplicity, we model the common resource as a physical (i.e. spare) component, though the implications are the same for repair-service capacities. The repair inventory, then, consists of spare-part inventories of supplier-specific components and one

* Corresponding author.
E-mail address: changmuk.kang@ssu.ac.kr (C. Kang).

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common component. This configuration is similar to that of an assemble-to-order (ATO) inventory or a serial newsvendor network [4,14,16,19,46].

We find an industrial example that is consistent with our problem settings in solar photovoltaic (PV) module manufacturers. A PV module is an end product that produces electricity from sunlight, which is a representative sustainable-energy source. It is required to last up to 25 years, but PV module manufacturers suffer from uncertain supplier reliability [22]. A PV module is manufactured by first making a laminate of a protection glass, PV cells to generate electricity, and a backsheet to protect the cells from the outside environment. Outer frames are assembled to the laminate, and a junction box is attached to output generated electricity. We focus on a backsheet as a component that may cause product failure. It is an emerging issue in the solar industry to assure quality of the backsheet since it widely varies between suppliers [22,31]. If a backsheet fails to protect PV cells from UV, moisture, and weather conditions, the inside cells are permanently damaged. Thus, the manufacturer also requires spare PV cells in order to repair modules with defective backsheets. We can examine whether to source backsheets from a single or dual suppliers.

This paper provides distinctive implications from the existing literature for supplier diversification. As has been extensively studied in the supply risk literature, supplier diversification reduces supply variance on the principle that the probability that all suppliers are defective, low yield, or disrupted is smaller than in the case of a single supplier (see the detailed literature review in Section 2). We found that in addition to this variance reduction advantage, dual sourcing significantly reduces the expected repair cost because of the presence of the common component. It reduces the shortage cost by procuring some spare parts when it is too expensive to store spare parts for common and single sourced components. Meanwhile, if single sourcing stocks a strictly positive amount of spare parts, a smaller number of common-component spare parts may be required compared to dual sourcing since it is quite unlikely that both suppliers would be defective simultaneously. Without the common resource, single sourcing always takes a lower expected cost in spite of the concentrated risk since it pools spare-part demands that would be separated if dual suppliers were employed. We analytically proved properties of the repair inventories and conditions that dual sourcing realizes its benefit. We further numerically investigated when the benefit is maximized with respect to risk and cost parameters or overridden by single sourcing advantages such as choosing lower cost suppliers and pooling repair demands.

The remaining sections are organized as follows. Section 2 reviews the previous literature on supply diversification strategies and ATO models. Section 3 describes the model and formulates costs as a function of sourcing and inventory decisions. Section 4 shows the properties of the optimal spare-parts stocking quantity for a sourcing decision, and Section 5 undertakes a numerical investigation of optimal sourcing decisions under different parameter configurations. Section 6 concludes the paper.

2. Literature review

2.1. Diversification of supply risk

As noted above, adopting multiple suppliers is a strategy by which manufacturers can effectively mitigate the risks of supply uncertainty. Various kinds of supply risks and their mitigation strategies have been extensively studied (for a comprehensive review, see [39,20]). The specific supply-defect risk addressed in these pages is relatively new to the literature. Whereas several recent studies have investigated the causes and consequences of defects (e.g., [7,5,40]), the only study treating defect as a supply risk and proposing diversification as a mitigating strategy is that of Yim [51]. Yim [51] proposed a multiple-supplier procurement-allocation model that minimizes a risk-averse cost function that quadratically increases with the number of defects. Where a design error is responsible for defects, Kang et al. [23] showed that the defect risk is exponentially amplified where a common design is shared among different products. It also suggests risk-averse manufacturers to diversify suppliers in order to adopt their independent designs. The present study shows that diversification is also beneficial for risk-neutral manufacturers who adopt the expected cost as an objective function.

Among the other sources of supply risk, yield risk, which arises when a manufacturer receives only random amount of orders from suppliers, is closely related to, and encompasses, defect risk [18]. Earlier papers in this area showed that additional inventory is required under yield randomness (e.g., [21]) for infinite horizon periodic review, and that dual sourcing benefits from reducing variability of received orders (e.g., [17,29,2]) using the economic order quantity model, the newsvendor model, and the multi-period stochastic inventory model, respectively. Subsequent studies introduced additional factors that can account for the additional costs associated with a large number of suppliers, with a view to determining optimal procurement allocation among a number of potential suppliers. Agrawal and Nahmias [1] introduced a linear fixed cost for an increasing number of suppliers. Burke et al. [6], by contrast, assumed asymmetric costs for suppliers, implying, under dual sourcing, that certain units will be purchased from the more expensive supplier. Wang et al. [49] and Federgruen and Yang [11,12] looked at a single sourcing case as an opportunity to improve supplier reliability.

Recent studies discuss need for supplier diversification under disruption risk, which is a special case of yield risk. When a supplier is disrupted, in an occasional way, they cannot deliver any order at all for random periods. It is obvious that diversification is also an effective way to mitigate disruption risk [24]. Yu et al. [52] formulated stationary profit functions for normal and disrupted states of a supply chain and investigated when dual suppliers realize higher profit than a single supplier. Schmitt and Snyder [36] and Tomlin [41] provided analytical models to obtain the optimal inventory policies for single- and dual-supplier configurations and assessed value of adopting multiple suppliers. Sawik [32,33] solved selection problem of a supplier portfolio under disruption risk using mixed-integer programming models.

While the above studies assume that products from multiple suppliers are substitutable in meeting demand, the work of Tomlin and Wang [43] and Schmitt et al. [35] addressed the case that diversified suppliers break this substitutability. Then, dual suppliers have to face independent demand sources that could be pooled together if a single supplier is employed (the benefit of demand pooling, thanks to the seminal work of [9], is well known). Our model also takes into account this tradeoff, in that spare parts from different suppliers are not substitutable. Tomlin and Wang [43], by modeling and comparing network structures each of which achieves exclusively either supplier diversification or demand pooling, found that demand pooling is always preferable under the risk-neutral condition, whereas its benefit is diluted when suppliers are unreliable; accordingly, they reported that supplier diversification might be preferable for a strongly risk-averse manufacturer. Schmitt et al. [35] presented similar single/dual sourcing tradeoff implications under disruption risk, by a mean-variance risk-aversion approach. Schmitt et al. [34] had already stated that diversified supplier only reduces variance rather than expected cost. In this paper, we offer, in consideration of the expected cost measure in our ATO configuration, a quite

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