AFTER-SALES SERVICE CONTRACTING FOR EXCELLENCE IN LIFE-CYCLE COST MANAGEMENT: NUMERICAL EXPERIMENTS AND SYSTEMATIC REVIEW OF ANALYTICAL MODELS

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This research adds to the literature and provides insight to practice via three essays that increase understanding about the applications and consequences of the two new approaches to the after-sales service governance: warranty contract and performance-based contracts. First, we attempted to enhance our knowledge of the modeling of the after-sales service process. In the first essay, the research papers with analytical models of after-sales services to present current trends, issues, and future research directions in the literature are classified. In the second essay, the effect of the warranty contract on the supplier's product quality improvement efforts in the context of capital goods is examined. Three sets of optimization models reveal that the existence of a warranty improves product quality. In the third essay, the performance-based contract is examined in the context of the warranty contract. The numerical experimentations conducted demonstrate that the performance-based contract is superior to the warranty contract in terms of the supplier's product quality efforts and the customer's total cost of after-sales services. The alignment of incentives based on the product performance tackles the issues presented in the traditional after-sales service contracting. Collectively, the three studies presented in this research expand our understanding of after-sales service contracts. Thus, the research presents managerial implications and adds to the existing body of knowledge in after-sales service research.

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INTRODUCTION

Background

After-sales support service has gained significant attention in both the managerial practice and academic literature. When handled well after-sales support service provides a potential source of profit for suppliers. In fact, after-sales support services can generate twice or three times as much value than actual product sales (Kim et al., 2007; Randall et al., 2010). In 2006, revenue generated from after-sales support services was approximately $1 trillion and represented 8% of the gross domestic product in the US (M. A. Cohen et al., 2006; Mirzahosseinian et al., 2016). An Accenture (2003) study shows that General Motors generated $2 billion profit from $9 billion after-sales services, more than the profit generated from $150 billion sales(Kim et al., 2007; Mirzahosseinian & Piplani, 2011). From the buyer's perspective, however, after-sales support service is a significant source of expenses. According to the Department of Defense (DoD) 2003 study, after-sales support cost of defense systems represents 80% of logistics service spending of DoD(Sols et al., 2007). The US airline industry spends $40 billion annually on after-sales support services (Flint, 2007; Randall et al., 2011).

The imbalance between the supplier's profit and the buyer's cost drive supply chains to create more effective governing structures to manage after-sales support provided by the supplier and consumed by the buyer. One approach is the development of a contract as a governing structure and different types of contracting mechanisms are studied in an effort to find a more effective governing structure. Two types of after-sales support contracts have gained recent attention: resource-based contract (RBC) and performance-based contract (PBC) (Kim et al., 2017; Öner et al., 2010). Especially for complex systems in aerospace, defense, and manufacturing industries, there is a shift from traditional resource-based contracting to new performance-based contracting (Hypko et al., 2010b; Kim et al., 2007). The number of PBC applications in the defense industry increased in the last decade (Nowicki et al., 2008).

Performance-based contract -sometimes called an outcome-based contract, pay-for-performance, or performance-based logistics- is a governance mechanism that incentivizes suppliers based on realized outcomes rather than material spent for after-sales support service. Recent studies on PBC have four main stream developments: (1) theoretical development, defining frameworks for PBC implementation (Guo & Ng, 2011; Hypko et al., 2010a; Randall et al., 2010; Sols et al., 2007) ; (2) understanding the structure of PBC with case studies (Datta & Roy, 2011; Fallah-Fini et al., 2012; Hensher & Stanley, 2003; Ng et al., 2009; Ng & Nudurupati, 2010); (3) benefits and effectiveness of PBC (Doerr et al., 2005; Hypko et al., 2010a; Randall et al., 2011, 2015; Sols et al., 2008); analytical models for finding optimal inventory and investment level under PBC (Jin & Tian, 2012; Mirzahosseinian & Piplani, 2011; Nowicki et al., 2008; Öner et al., 2010); (4) analytical models for finding optimal contract parameters for PBC (Kim et al., 2007, 2017; Plambeck & Zenios, 2000).

Most of the studies on after-sales service contracting focuses on performance-based contracting. For after-sales service contracts, however, there are numerous different contract types to be studied analytically; including, but not limited, to product warranty contracting, procurement warranty contracting, and service contracting(D. Gupta et al., 2011). The review of the literature posits that after-sales service contracting research fails to focus on warranty contracts.

Warranty contracts require suppliers to improve product reliability with design and corrective maintenance schedules during the specified timeline. Warranties provide incentives to meet agreed minimum requirements (D. Gupta et al., 2011). The issue of supplier behavior, namely spare part allocation and reliability improvement, needs to be analyzed to compare warranty contracts with performance-based contracting.

While warranty contracts drive suppliers to carry out base requirements, performance-based contracts provide incentives for suppliers to improve the design and perform periodic preventive maintenance for better life-cycle cost management. Performance-based contracts give avenues to suppliers on exceeding the expected performance(D. Gupta et al., 2011). Research on comparing warranty contracts and the performance-based contract could provide a better understanding of how performance-based contracting better incentivize supplier.

Finally, a comprehensive systemic review of published analytical modes of performance-based contracting would provide future research opportunities. Moreover, the systemic review would help on identifying the gaps in the body of performance-based contracting knowledge to develop useful models.

Consistent with the need for the research of after-sales service contracts, a set of analytical models with numerical experiments and a systemic review of existing models would contribute to understanding how contracts affect supplier behavior in the after-sales support services industry.

Problem Statement

The issues regarding after-sales service contracting are addressed in the context of the supplier's decision-making process because the outcome of the contractual relationship depends on supplier decisions. According to agency theory, the outcome of PBC is a function of behaviors that is under the control of the supplier (Whipple & Roh, 2010). Therefore, a better understanding of suppliers' decision-making process is critical for better after-sales support contracts.

One fundamental premise of agency theory states that a constant wage would give the agent full insurance but no incentive. Paying an agent based on certain outcomes, on the other hand, would give full incentive but no insurance (Gibbons, 2005). Without any insurance, an outcome-based contract puts the risk on the supplier (Eisenhardt, 1989). Therefore, from the agency theory perspective, a risk-averse buyer would be more interested in outcome-based contracts (Hypko et al., 2010b). Similar findings are provided on after-sales service contracting regarding the risk-sharing issue. PBC for after-sales services shifts the risk to the supplier (Kim et al., 2007; Nowicki et al., 2008), responsibility for product performance switches from buyer to the supplier (Randall et al., 2010). Moreover, Kim et al., (2007) find that PBC is not the optimal contract when a supplier is risk-averse. For capital goods transactions, PBC could be detrimental for a supplier in a principal-agent relationship (Hünerberg & Hüttmann, 2003). Therefore, a supplier's behavior should be investigated more to evaluate outcomes of PBC.

Optimal supplier decision under PBC has been studied analytically. Nowicki et al. (2008) provide an optimization model for spare parts inventory decisions for multi-item, multi-echelon after-sales service. Öner et al. (2010) develop an analytical model to find optimal supplier decisions regarding spare parts inventory and reliability improvement based on maintenance cost, design cost, and production cost. Mirzahosseinian and Piplani (2011) propose an inventory model to analyze the trade-off between spare parts inventory level, product reliability improvement, and repair efforts under PBC. In their optimization model, Jin and Tian (2012) investigate the effect of usage rate on optimal inventory and reliability levels. In another analytical study, Jin and Wang (2012) analyze the effect of failure rate and fleet size on the aforementioned optimal supplier decisions. Finally, Kim et al. (2017) analytically compare the optimal supplier decision under RBC and PBC. None of the studies, however, investigate the effect of warranty contracting in after-sales services and compare warranty contracting to the performance-based contracting.

Before studying the warranty contracting, we need to review after-sales service contracting literature and analytical models in after-sales service contracts. A literature review expands our knowledge of existing analytical models and relevant assumptions on after-sales service contracts. Our literature review shows that numerical experimentation is a valuable part of the analytical models. Most of the PBC models mentioned in the previous paragraph have two common variables that are subjected to supplier decision: spare parts inventory level and reliability improvement level. There is a need for finding optimal values for the two variables with an optimization model. A numerical analysis would help to better understand the supply chain model of interest. Kim et al. (2017) provide a very powerful game-theoretical model for finding optimal inventory level, reliability level, and contract parameters for RBC and PBC, but they don't include a numerical analysis that compares warranty contracting and PBC IN their model. Therefore, there is a need for the development of a simplified, supplier focused model with numerical analysis to investigate warranty contracting and PBC.

Research Question

First, we need to evaluate existing analytical models on after-sales service contracting to build an optimization model in the capital goods context. Second, an optimization model for supplier profit needs to be solved and the decision variables of the optimization model need to be evaluated with the numerical experiments to investigate the role of the contracts on supplier behavior. Specifically, inventory level and quality improvement efforts of the supplier need to be calculated with industry-specific data under a warranty contract and performance-based contract. Therefore, we provide the following three research questions: (1) What are current trends in the mathematical modeling of an after-sales service process? (2) What is the effect of the warranty contract on product quality improvement efforts of the supplier under the after-sales service context? (3) Compared to the warranty contract, how would performance-based contracting perform better on incentivizing the supplier on investing more in product quality?

Purpose and Contribution

One main purpose of the proposed studies is to develop an optimization model and valid measurements for decision variables in the after-sales support services industry that contribute to buyer's cost savings and profit. The other main purpose of these studies is to present the current research activities on the analytical modeling of after-sales service processes. This research contributes to the theoretical body of knowledge, managerial practices, and academia.

One of the purposes of analytical models on operations management is to test and clarify existing theories. This study contributes to the theoretical body of knowledge on performance-based contracting and warranties contracting by offering a set of optimization models for after-sales service context to validate, clarify, and to refine existing models. This study explores how warranty contracting and performance-based contracting are conceptualized on operations management and their effects on supplier decisions are numerically demonstrated in a set of optimization models. Given the specific scenario in the aerospace industry, analytical models explore how a payment structure within a specific contract influences supplier decisions measured as funds invested in spare part inventories and product quality improvement efforts. Also, the numerically investigated models provide insight for forming practical guidelines for after-sales support buyers based on an understanding of factors influencing supplier decisions.

Research Design

This research contains three studies that focus on supplier behavior that contributes to supply chain cost. The contribution is both in the area of product quality, cost reduction as well as the warranty in the capital goods industry. Essay 1 classifies existing research papers to present current research trends in after-sales service modeling. The categorization process of the papers reveals that there is a need for numerical experimentations with real-life data in after-sales service contracts. Essay 2 develops an optimization model to investigate the relative contribution of the warranty contract to the supplier's product quality improvement efforts. The findings suggest that the warranty contract is an effective way of leading the supplier to improve product quality. Essay 3 develops an optimization model to compare the warranty contract with the performance-based contract. The numerical experimentations present that the performance-based contract is the best option to incentivize the supplier on improving product quality.

Organization of the Dissertation

This research includes an investigation of two after-sales service contracting and analytical models in the after-sales service literature. The manuscript begins with the discussion about the current trends, issues, and mathematical models on after-sales service contracting, following by two optimization models and discussion on contribution. The first essay extensively investigates the peer-reviewed scientific journals to categorize analytical models of after-sales services scientifically. The second essay utilizes an optimization model to examine the ramifications of warranty contracting on the product quality improvement efforts of an after-sales service provider. Building on modeling assumptions of the previous essay, the third essay juxtaposes performance-based contracting with the warranty contracting in terms of product quality improvement efforts and spare parts inventory provisioning. Besides the first essay, each essay has a dedicated literature review, modeling assumptions, solution algorithms, numerical experimentations, and results section that are separately presented. Finally, the last chapter discusses the summary of findings, contributions, and future research directions made by the three studies.

ESSAY 1

OPTIMIZATION MODELS IN AFTER-SALES SERVICES: A LITERATURE REVIEW

Introduction

After-sales services and the associated activities have grown considerably in focus during recent years along with the management of the after-sales process. However, during the last two decades, after-sales services are potentially viewed as a forgotten part of the supply chain. In some industries, including a few exceptionally large multinational and electronic manufactures, after-sales account for a large portion of profit so all firms need to consider the relevance to their environment. For example, after-sales services account for more than half of the corporate profit at Siemens, General Electrics, and Honeywell International (Govindarajan & Immelt, 2019). Therefore, a fuller understanding of the after-sales services is needed despite the great attention from academic and managerial research.

Consistent with the importance of after-sales services, corporations are experiencing a growing dependence on after-sales services to increase profits. In 2010, 75 percent of incomplete orders of General Electrics were from service contracts which value around 170 billion dollars: a contribution of 80 percent to industrial earnings(Govindarajan & Immelt, 2019). Although after-sales services are becoming more crucial for overall company success, even big companies fail to offer better after-sales services. According to an Accenture survey, in the year 2013 alone, two-thirds of the customers switched their current service provider due to poor after-sales support (Pearson, 2015). The aforementioned case on the GE posits that researchers and practitioners should focus on enhancing knowledge on after-sales services for greater success.

Over the last three decades, an increased level of competition among the manufacturers and service providers have made after-sales services an essential part of a marketing strategy. Many companies come up with unique after-sales strategies to differentiate themselves from other competitors. For example, a 12-month warranty duration with 1000 flight hours was a common marketing strategy for airplanes around the 1980s. With the technological developments, airline manufacturers extended their after-sales service strategy of warranties up to 10 years coverage (Shafiee & Chukova, 2013). One aerospace engine manufacturer took the after-sales service strategy one step ahead and offered customers a charge based on the product usage, rather than product itself. The strategy, called 'power by the hour', differentiated the engine manufacturer from the competitors by offering a novel after-sales service (Kim et al., 2007). A similar observation can be made for automobile manufacturers. While the industry standard for automobile warranties was 3 year/60,000 miles in the 1980s, today many automobile manufacturers offer a 5 year/100,000 miles warranty. Today, one manufacturer has started to offer a 5 year/unlimited mileage warranty in Canada (Toljagic, 2018). With extended after-sales service offerings, manufacturers are responsible for product failures due to quality problems, design problems, and excessive usage.

A higher level of after-sales service can increase the demand, but it introduces a significant amount of extra servicing cost to the expenses to the manufacturers. Traditionally, after-sales services were perceived as extra cost generator. In today’s competitive market, however, this perception has changed (Rezapour et al., 2017). With increased access to the information, customers make their purchasing decision not only on the products themselves but also the services offered with the product. The industry leaders recognized that offering valuable after-sales service is as crucial as selling a product. As after-sales services directly interest the company profit, constructing a sound service offering strategies to increase profit and reduce service costs has emerged as an important issue to the manufacturers and service providers. One possible way to generate strategies for profit maximization or cost minimization is by utilizing analytical models for better decision making.

Besides effects on demand and profit, after-sales service is a key factor for product reliability, customer satisfaction, and product availability. Therefore, an after-sales service decision will affect various aspects. A good analytical model will help decision-makers to evaluate the effects of after-sales service outcomes. In the literature, researches have provided various analytical models to determine good practices of after-sales services. Each analytical model utilizes different modeling tools to find the best results. Based on the extensive research, we first categorized analytical models according to the utilized modeling tool. After-sales service models are classified into three broad categories: game theoretical models, goal programming models, and simulation models. Game theoretical models investigate cases where decisions of multiple parties affect the outcome for each party. In an after-sales service supply chain, both decisions of suppliers and customers, or decisions of manufacturer and retailer, alter the outcome for every part of the supply chain. Thus, game theoretical models analyze interactive after-sales service optimization problems. A comprehensive study on the applications of game theory on the analysis of supply chain topics can be found on Cachon and Netessine (2004). Some examples of game theoretical models in after-sales services are included in performance-based contracting (Bakshi et al., 2015; Jin et al., 2015; Kim et al., 2010; Lin et al., 2016), warranty (N et al., 2017), and manufacturer retailer relationship analysis (Kong et al., 2017; Kurata & Nam, 2010; Wu, 2011). Goal programming is an analytical tool to solve multi-objective optimization problems. Goal programming in this study, however, encompasses a broad range of optimization models including but not limited to linear programming, genetic algorithm, heuristic models, etc. that does not fall into game theoretical models. In after-sales service literature, goal programming extensively used in life cycle cost analyzing (Hartwig et al., 2015; Jin & Tian, 2012; Öner et al., 2010; Zhang & Chen, 2019), maintenance operation problems (Basten et al., 2012; Bijvank et al., 2010), evaluation of performance-based contracting (Jin & Wang, 2012; Mirzahosseinian et al., 2016; Öner et al., 2015), and product-service systems investigations (Pascual et al., 2017; Shokohyar et al., 2014;

Wenming Xie et al., 2016). Simulation models are another powerful tool to analyze problems in a supply chain environment. With the help of mathematical configurations, simulation models utilize computer software to analyze approximate replica of real supply chain structures to solve complex problems. Jahangirian et al. (2010) provide a literature review for simulation models used in manufacturing and other business environments. Applications of simulation models in after-sales services can be found in product-service system analysis (Alabdulkarim et al., 2015; Chalal et al., 2015) and service design problems (Owida et al., 2016; Visintin et al., 2014).

The research on after-sales service has extensively used the analytical tools mentioned in the previous paragraph. From 2010 to 2019, both after-sales services and analytical models—game theoretical models, goal programming models, and simulation models—in after-sales services have drawn growing attention from the scientific and managerial community. During the last decade, studies on after-sales service include three books, more than 20 magazine articles, and more than 250 scientific articles based on only the EBSCOhost Business Source Complete database. With additional database searches, this study reviews the peer-reviewed scientific articles on after-sales services and focuses on the analytical models.

The papers deal with an in-depth review of after-sales services that are very scarce. The existing studies focus on specific topics rather than focusing on specific methodologies. For example, Selviaridis and Wynstra (2015) provide a systematic review of performance-based contracting for future research direction. Some reviews focus on analytical models in warranty. For instance, Murthy and Blischke (1992) investigated mathematical models in warranty and categorized them based on decision-makers. Another study by Shafiee and Chukova (2013) analyzed analytical models in warranty and maintenance. This study takes the same approach applied in Shafiee and Chukova (2013) and implements it on the after-sales service context. To the best of our knowledge, this paper is the first attempt to review analytical models used in after-sales service research. A categorization procedure is provided to classify the scientific articles published between 2010 and 2019. More than a thousand papers were found based on the multiple scientific database searches and each paper reviewed. After the first initial review, sixty-five articles were selected according to relevance and research methodologies. The final list of papers for extensive review filtered on the criteria of relevance to after-sales services and categorized into three main classes: game theoretical models, goal programming modes, and simulation models.

The rest of the paper is structured as follows: first, we described the categorization procedure used in this study. In the third section, research articles with analytical models in after-sales services are investigated and the findings of the categorization process are presented. In the final section, we provided the conclusions with the future research directions.

Categorization Procedure

Categorization Technique

The research on after-sales services is scattered around various disciplines including management, supply chain, logistics, and engineering. Thus, it is challenging to limit our research to a specific discipline. Therefore, we used multiple online databases to find academic literature related to after-sales services. Following online scientific journals, databases were used with text mining methodologies to provide the articles on after-sales service models.

EBSCOhost Business Source Complete, ProQuest ABI/INFORM Global, Emerald Insight, Clarivate Analytics Web of Science, INFORMS PubsOnLine, EBSCOhost Academic Search Premier, ScienceDirect Journals, Wiley-Blackwell Journals, IEEE Xplore, Taylor and Francis Online, INDERSCIENCE Online, and Elsevier Journals.

The text mining technique used in this study is utilizing the advanced search algorithm of online databases. The following steps are applied to each online database:(1) Three descriptors—"after-sales service", "after-sales support", and "product-service system"—

selected as main search terms based on the preliminary literature review. The three descriptors used with the "OR" function, so any article includes one of them presented at the text mining result. (2) Since practitioners and academic scholars generally use scientific journals to obtain information and distribute new findings; masters' theses, doctoral dissertations, conference proceedings, working papers, and textbooks are excluded from applying 'only scientific journals' filter to text mining tools. (3) Also, two other filters, 'last 10 years' and 'English language', are applied to limit the article to only English articles published in the last decade. The first set of database searches produced one thousand one hundred and sixty-five articles. Then, the abstracts of each journal were reviewed to eliminate the articles that are not related to after-sales service. After the review of abstracts, the full text of articles reviewed to choose the articles with analytical models. As a result, we selected sixty-five articles published in twenty-nine different scientific journals for the categorization procedure.

Selection Process and Evaluation Structure

The final selection of sixty-five articles reviewed in-depth and categorized according to the categorization structure in four different phases. First, we conducted multiple online database searches. Second, we performed the initial categorization based on abstract reviews. Third, from the selected set of articles after initial categorization, we reviewed full text to evaluate research methodologies used in the articles. Finally, the articles which have game theoretical models, goal programming models, or simulation models selected for the final categorization process. The selection process and evaluation structure are provided in Figure 1.1. The final selection of articles was evaluated according to the after-sales service model they have, according to the scientific journals in which the selected articles published, and according to publication years.

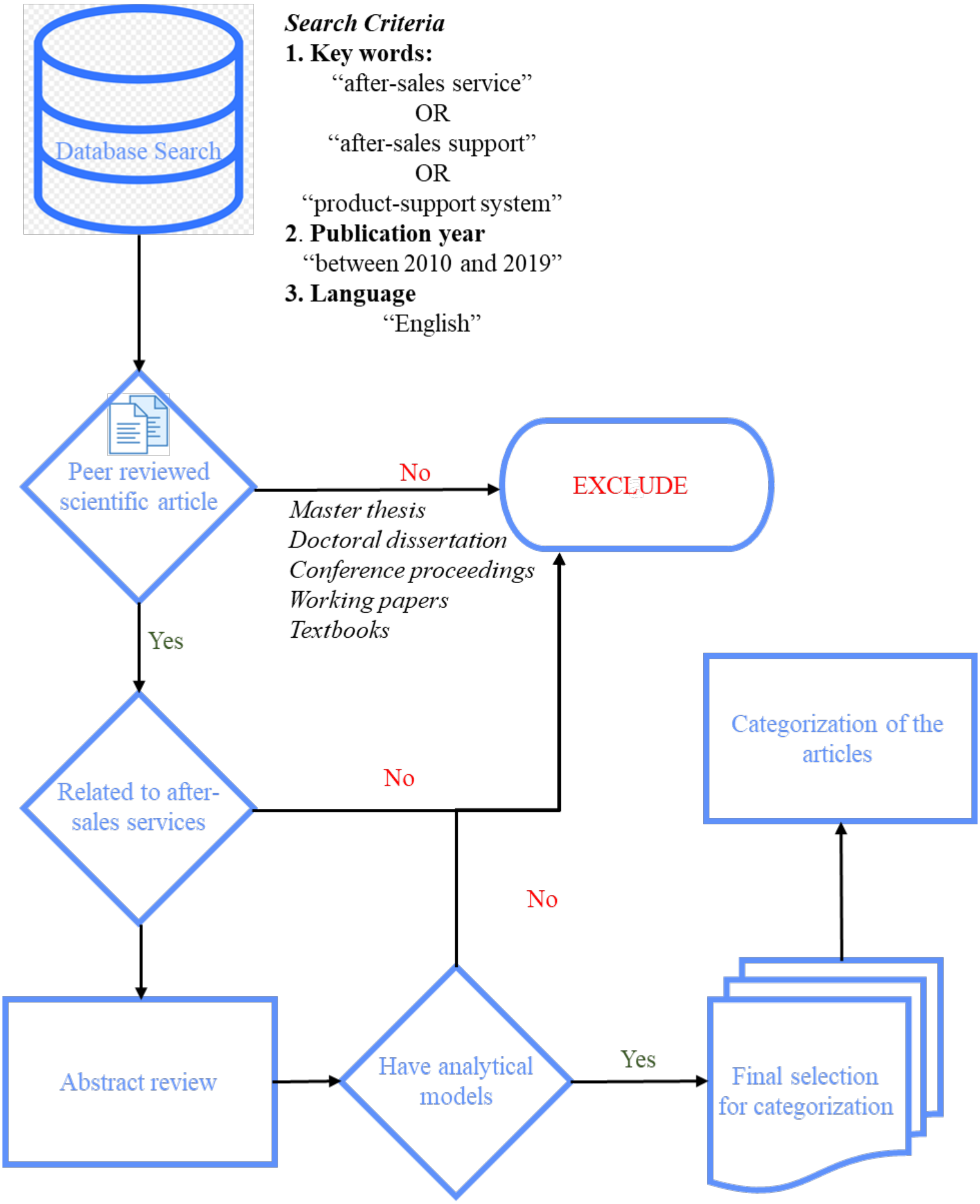

Figure 1.1: Selection process and evaluation structure

The distribution of selected articles according to the publications is presented in Table 1.1. The final selection of articles is dispersed throughout the twenty-nine journals. Of these, the *Journal of the Operational Research Society*, which examines the development of research methodologies, practices, and theories and research in operational research, contains the largest portion of the articles with 19.92% of the selected articles, ten of sixty-five articles. The second-highest portion is the *European Journal of Operational Research* with 13.43% (nine of sixty-five articles) of the total.

Table 1.1: Distribution of Selected Articles According to the Publications

No	Journal	Amt	%
1	Journal of the Operational Research Society	10	15.38
2	European Journal of Operational Research	9	13.85
3	Annals of Operations Research	8	12.31
4	Production and Operations Management	5	7.69
5	International Journal of Production Economics	4	6.15
6	International Journal of Production Research	4	5.97
7	Industrial Management & Data Systems	3	4.62
8	Journal of Intelligent Manufacturing	3	4.62
9	Management Science	2	3.08
10	Geneva Risk and Insurance Review	1	1.54
11	International Journal of Modelling in Operations Management	1	1.54
12	International Journal of Engineering and Manufacturing	1	1.54
13	Asia - Pacific Journal of Operational Research	1	1.54
14	Computers & Industrial Engineering	1	1.54
15	Central European Journal of Operations Research	1	1.54
16	Artificial Intelligence for Engineering Design, Analysis and Manufacturing	1	1.54
17	International Journal of Services Technology and Management	1	1.54
18	Multimedia Tools and Applications	1	1.54
19	Journal of Manufacturing Technology Management	1	1.54
20	Journal of Decision Systems	1	1.54
21	Mathematical Problems in Engineering	1	1.54
22	Nankai Business Review International	1	1.54
23	Operations and Supply Chain Management: An International Journal	1	1.54
24	PLoS One	1	1.54
25	The International Journal of Advanced Manufacturing Technology	1	1.54
26	Total Quality Management & Business Excellence	1	1.54
TOTAL		65	100

The distribution of articles by publication year is provided with the Figure 1.2. The graphical representation shows that the number of publications for each year has increased over the years. The highest number of publications with analytical models related to after-sales service can be observed in 2017 with ten articles.

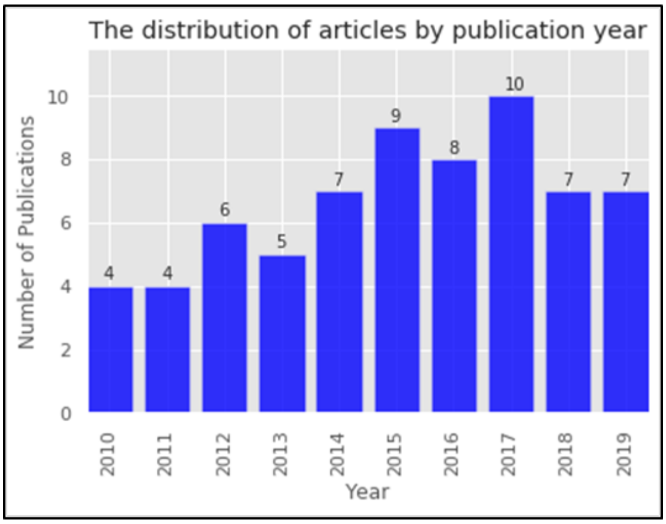

Figure 1.2: Distribution of articles by publication year

Categorization Structure

Before the review, we first introduce a categorization structure to classify the articles according to the type of analytical models. First, we proposed to organize the literature involving after-sales services into three main classes:

(1) After-sales service models solved with game-theoretical approaches. The articles in this class utilize game theory to find answers for after-sales service problems. One big advantage of the models in this class is they focus on both supplier and buyer decisions to find an optimal solution.

(2) After-sales service models solved with goal programming techniques. These articles use goal programming techniques including genetic algorithms, linear programming, heuristic approaches, and global optimization to find the optimal decision values within the given constraints. The models in this class generally focus on cost minimization or profit maximization.

(3) Simulation models in after-sales services. The papers in this class tackle more complex problems to provide decision support systems regarding after-sales service systems. While some papers provide initial mathematical models before simulation applications, some papers use simulation software for problem solutions.

We present the detailed categorization structure of analytical models in after-sales service in Figure 1.3.

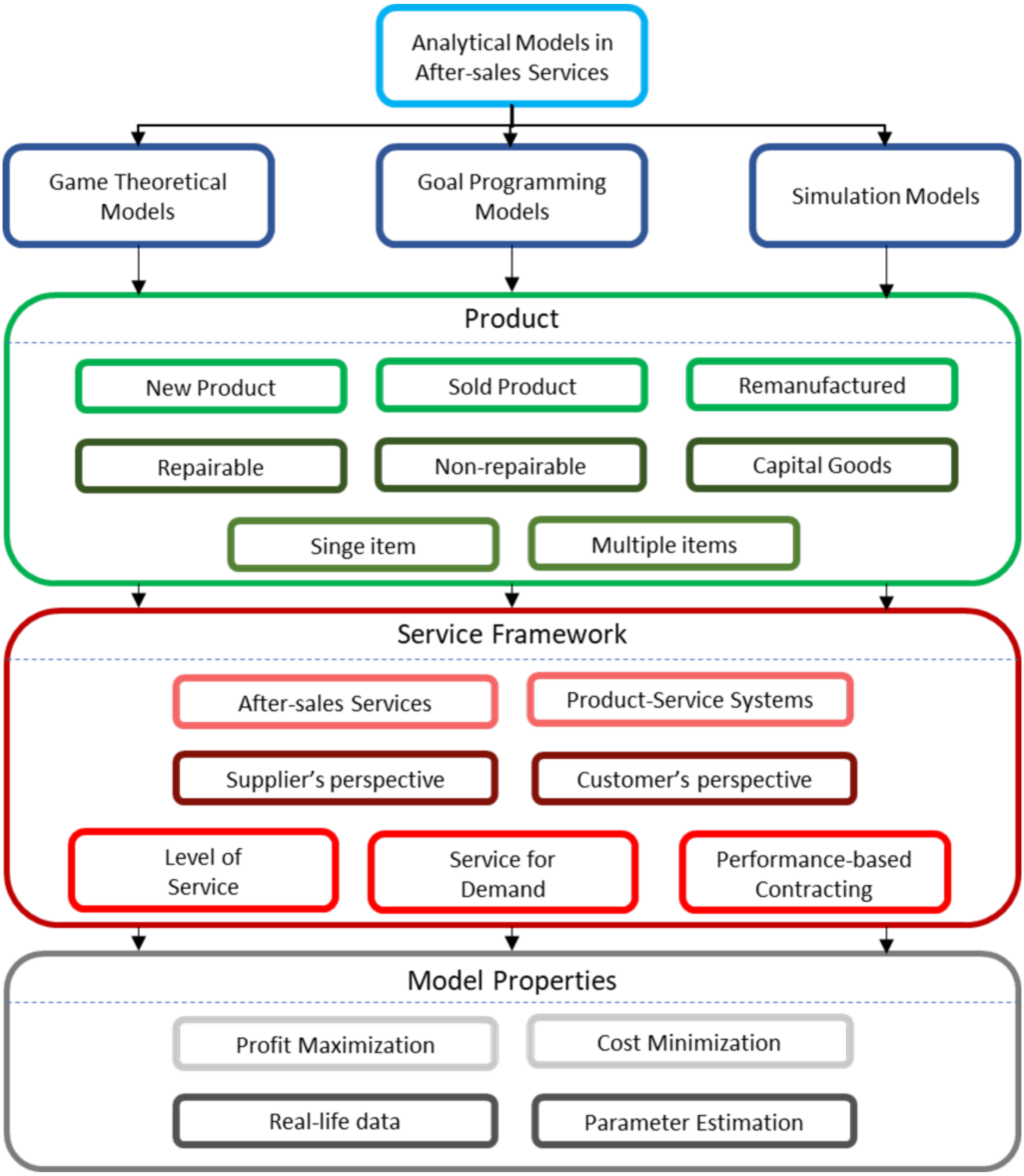

Figure 1.3: Categorization structure

Categorization of the Articles

Among the three main classes, 'after-sales service models solved with goal programming techniques' consist of almost half of the articles (32 out of 65 articles which reflects 47.73% of the total amount). 'After-sales service models solved with game-theoretical approaches' has the second-highest portion with 38.36% of the total publications (25 articles). Simulation models consist of only 12.30% of the articles with only eight publications.

Distribution of Articles by Product Type

In this section, we used the classification technique for product warranty provided by Shafiee and Chukova (2013) and applied the technique on after-sales service models. We first look at if the after-sales service is applied to a new product before it is sold, a product that has already been sold, or a remanufactured product. Second, we categorized the papers according to repairable, non-pairable, or complex capital goods. Finally, we checked whether the model focuses on multi-item or single-item problems.

After-Sales Service for New Product / Sold Product / Re-Manufactured Product

In this section, we categorized after-sales service models according to the product status. Shafee and Chukova (2013) categorized warranty models as a new or second-hand product. Similarly, we evaluated whether the paper focused on a new product or used product. As the name of the topic suggest, after-sales service is generally provided for used product. However, after a brief review of the literature, we identified that after-sales service research does not only focus on the sold product but also a part of a new product to enhance the demand for new and remanufactured products. Therefore, we came up with three classes based on product status: After-sales service for new products, after-sales service for re-manufactured products, and after-sales service for sold products. The categorization results show that only a few of the researchers studied modeling after-sales service for the remanufactured products (five out of sixty-five articles, 7.7%).

For new products, after-sales service used as a tool to influence customer demand in various models. These models focus on optimal after-sales service for customer satisfaction (Kurata & Nam, 2010, 2013; T. Wang et al., 2019), optimal pricing and service level to increase customer demand (Cheng & Shu-yi, 2014; G. Li et al., 2014; S. Li et al., 2016; Roy et al., 2018; Sun et al., 2019; Wu, 2011), design for the better product quality and reliability (Bakshi et al., 2015; Jin & Wang, 2012; Öner et al., 2010), contracts to govern the retailer's service level (Lan et al., 2017; Wenming Xie et al., 2014), and the factors -including after-sales service- that affect the success of a newly released product (Yenipazarli, 2015).

For used products, most of the models focus on spare parts, maintenance, and product quality for effective after-sales service management. Besides spare part, maintenance, and reliability, models in this category investigated product usage rate(Jin & Wang, 2012; Pascual et al., 2017; Sharma & Garg, 2012; Uvet et al., 2019) , decision making structures—centralized, joint, decentralized—(Basten et al., 2012; Selçuk & Agrali, 2013; Wei Xie et al., 2014) , after-sales service after the production halt of the item(Shokohyar et al., 2014), and service network design (Altekin et al., 2017; Nowicki et al., 2012).

In terms of remanufactured products, most of the models incorporate remanufacturing and remanufactured products as a part of the profit maximization problem. There is only one study that investigates the effect of after-sales service on the demand of a remanufactured product (Zhu et al., 2016).

Our categorization reveals that most of the after-sales service model on new products address after-sales service as a marketing strategy that alters demand. For used products, the models focus on spare parts, maintenance, and product quality to reduce the after-sales service cost. Remanufacturing is a strategy for reducing cost, but more research on the service of the remanufactured product would enhance our understanding of its financial and environmental impacts.

Repairable/Non-Repairable/Capital Goods

Models with repairable products use at least one repair variable in the analysis. In the case of non-repairable products, failure on the product cannot be redressed due to either the product has not been sold yet or the product is not repairable in nature. When the product is not repairable in nature, the service provider offers other options like a free replacement or free returns. Capital goods are a complex system that requires a high level of after-sales service to operate efficiently. Complex manufacturing equipment, commercial airplanes, high technology weapon systems, baggage claim belts are some examples of capital goods.

After-sales service for capital goods is a new topic and mostly studied under performance-based contracting. Out of sixty-five articles, only ten of them focus on capital goods (15.38% of total). Almost all models on capital goods have at least one repair variable. Therefore, we will include the discussion on capital good models blended with the repairable products model.

Models with repairable products used in twenty-five of the total articles (38.46% of the total). In this class, the models have at least one component regarding repairs. If a model does not have repair as a variable, we excluded it from this class. One model in this category studies the repair kit issue to find an optimal number of repair kits in the best locations (Bijvank et al., 2010). Repair cycle time is another variable that used extensively in after-sales service models (Jin et al., 2015; Jin & Tian, 2012; Öner et al., 2010; Selçuk & Agrali, 2013). Repair cycle time can be seen under different names like the speed of repair or repair lead time. The models with repair cycle time show that repair cycle time adds additional cost to the objective function as it decreases the availability of a product. Another repair variable that is used on the models is the cost of repair. Models in this category incorporate the cost of repairing resources to meet the desired level of repair constrains (Basten et al., 2012; Öner et al., 2015) or to find optimal service outsourcing strategies (I. Cohen et al., 2017). Repair capacity decisions and the number of repairs for capacity planning are other variables analyzed with simulation models (Sharma & Garg, 2012; Simmons, 2013) . Repair efficiency is also used as a predictor of optimal effort and order quantity for wind turbine maintenance systems (Ling Liang et al., 2017). Finally, repair overcharge for warranty fraud is another factor that solved with a game-theoretical model (N et al., 2017).

Non-repairable product class includes models that have not a repair related variable. First, if after-sales service used a demand changing factor in the model, we categorized them as a non-repairable product even though the product might be a repairable one. Second, products due to nature that has not repairable components added to this category. One model assumes that the supplier practices replace only policy for a non-repairable part to increase the reliability of a product under product-service offering that buyer charged based on the product usage rate (Pascual et al., 2017) . Another model compares three warranty policies -return only, replacement only, and both of them- for a non-repairable product (Rezapour et al., 2017). One thing we need to note is that we included service in the non-repairable category as well. One model inspects the quality of after-sales service of insurance service. Built as a multi-stage game-theoretical model, this paper analyzes the effect of after-sales competition and after-sales reputation for better customer satisfaction (Fedele & Tedeschi, 2015). Another model aims to find optimal service quality rather than product prices and service prices (X. Li & Li, 2016). Some models address a decision support model to categorize a product as non-repairable or repairable. One of these models compares four different strategies for product end of life stage: re-manufacture, repair, dispose, or recondition (Shokohyar et al., 2014). Similarly, another model compares two different service models, repair model, and replacement model, to increase the level of remanufactured product demand (Zhu et al., 2016).

One remark we need to make in this categorization is only two of the articles considers repairable and non-repairable together in the model. Most of the models evaluate repairable and non-repairable independently. In practice, an after-sales service model includes both repairable and non-repairable section. Therefore, more research should include repairable and non-repairable parts together, especially for the capital good models.

Single Item/Multiple Items

In this section, we evaluated the models based on the number of products that used failure rate, total cost, demand, or service level estimations. If a model uses single demand values, single failure rate, or total cost for a single product, we categorized the model to a single item class. If a model provides multiple demand variables, different failure rates for different parts, or multiple units on calculating the total cost, we categorized the model into multiple items class. Most of the models solve the problems by using only a single product. Only thirty-seven percent of the articles (24 of the 67 articles) are related to multiple items while sixty-three percent is about a single item.

In terms of multiple item models, one model uses the expected number of failures of each component differently on a system to find minimum after-sales cost while meeting the desired availability level (Basten et al., 2012). Another model adds the total number of systems to find an aggregate failure rate of all systems under the performance-based contracting (Jin & Wang, 2012). This type of model is more practical in the industry because when a customer contacts a supplier for after-sales service, the supplier covers all parts of the system and every system that the customer has. One model in this class attempt to increase the computational accuracy of multi-item spare parts inventory decision with a heuristic algorithm (Nowicki et al., 2012). The joint decision of spare parts inventory and investment on reliability improvement is investigated for each part of a capital good to minimize total after-sales service cost (Selçuk & Agrali, 2013). One model studies the redundancy of multiple components in a system along with the spare parts inventory level to maximize system availability under centralized decision making (Wei Xie et al., 2014). Finally, a set of models adds the size of systems under the after-sales service to the analysis to find the effect of the number of products on the service cost (Jin & Tian, 2012; Mirzahosseinian et al., 2016; Uvet et al., 2019).

In the case of single-item models, one model that needs to be pointed out uses a single failure rate to investigate the effect of service lead time on system availability under an after-sales service contracting (Kim et al., 2010). Most of the models that use after-sales service to increase demand consider a single price or single unit cost. For example, Wenming Xie et al. (2014) employ single product price and service level as variables and search for an efficient product-service system that maximizes the profit of both customer and manufacturer. One exceptional study we need to mention in demand enhancing models group analyzes a manufacturer-retailer relationship with two different retailers and two products, different prices, and different service levels for each product on the investigation of a simple price discount contract (Sadjadi et al., 2018).

Extending the models for a single item to multi-items provides future research avenues for both academicians and practitioners. Some papers include this issue in their discussion section that their model can be improved by applying multi-item criteria (Kim et al., 2010; Yenipazarli, 2015) or multiple-suppliers (Zhang & Chen, 2019).

Distribution of Articles by the Service Framework

In this part, we categorized the articles based on the service framework used in the models. First, we analyzed articles in two categories of service context: after-sales service, product-service systems. Second, we investigated the articles to identify whether the models solve the problem from the suppliers' perspective or the customers' perspective. Finally, we attempted to categorize the articles according to the service concept that the models analyze.

After-Sales Service/Product-Service Systems

In this part of the analysis we categorized the models according to after-sales service and product support systems. While most of the articles study after-sales services, only fourteen percent of them (9 out of 65) researches product-service systems.

After-sales services have become a source of income and a differentiation point in competitions in the modern industry. On the other hand, service provides needs to allocate resources for a set of after-sales activities like an inventory of spare parts, customer services, warranty costs, and so on. Most of the models on after-sales service focus on these resource-consuming factors. There are some models we want to mention in this category that considers factors other than the aforementioned cost generating factors. For instance, after-sales service competition between the manufacturer and retailer and extension of service competition models like after-sales service based on customer segmentation (Kurata & Nam, 2010) and uncertainty (Kurata & Nam, 2013) is interesting research avenues for future studies. After-sales service competition between multiple retailers or multiple manufacturers is another interesting research area. After-sales service outsourcing is another research area that goes beyond minimizing the cost factors of after-sales service. One model studies a retailer's decision on providing after-sales service in-house or outsourcing the after-sales service to a third-party service provider. The model provides insight on when outsourcing services would be beneficial and on the value of cost information sharing with the manufacturer when performing the services in-house (G. Li et al., 2014). Another model focuses on service outsourcing decisions under different manufacturer-retailer power structures (Bian et al., 2017). Finally, the contracting issue is another problem that studied on after-sales services. For example, one model investigates the effects of two different after-sales service contracts, namely resource-based contracting and performance-based contracting, on the supplier behavior for signaling hidden information on product reliability (Bakshi et al., 2015). Another contracting problem in after-sales service is the issue of excess stock after contract expiration. One model attempts to optimize spare parts inventory to refrain from excess stocks at the end of an after-sales service contract (Pinçe et al., 2015). Finally, in one study, after-sales service data is used in a machine-learning algorithm to facilitate future decisions on after-sales services (Ko et al., 2017).

The product-service system is a new marketing strategy that sells intangible services bundled with tangible goods. The product-service system does not require the customer to own the product to get and results from the product. Customers can utilize the product by sharing, partnership, or leasing. For instance, one simulation model compares the procurement option and leasing option of a copying machine. In the simulation, the manufacturer offers disposal, recycling, maintenance, and other reverse logistics activities along with the product (Kuo, 2011). Another product-service system model explores a manufacturer-retailer relationship where manufacturer leases product with additional maintenance and repair services as a product-service system. The model searches for optimal leasing duration and leasing price for a product-service system (Robotis et al., 2012). Lastly, one model attempts to determine the value of a product-service system by quantifying the manufacturer's product quality and the retailer’s service level. In this model, the relationship between the retailer and the manufacturer analyzed under franchise fee contracts, wholesale price contracts, and retail price maintenance contracts (Wenming Xie et al., 2014). Investigating different contractual scenarios under product-service systems may provide better insight into understanding product-service system structures.

Supplier's (Manufacturer's) Perspective/Customer's (Retailer's) Perspective

In this categorization, we analyzed models to find out whether the model is solved from the customer's perspective or supplier's perspective. The role of after-sales service varies according to the perspective of different parties in the relationship. For customers, after-sales service is an essential element of product life cycle duration. Effective after-sales service for a customer requires acquiring optimal service level at an optimal price. For suppliers, after-sales service is a source of income with a considerable cost factor that needs to be optimized. Out of 65 articles, 23 of them (35.4%) evaluate problems from both suppliers' and customers' perspective while 37 (57%) and 5 (%7.6) solve a supplier problem and a customer problem respectively.

One of the few papers on customers' perceptive focuses on a buyer's problem rather than a supplier's problem. In its model, the paper investigates two major problems for a service buyer: information asymmetry which is the unknown cost of services, and non-contractible quality of the service. The model attempts to offer contract parameters for a service buyer to eliminate the effect of information asymmetry and service quality (X. Li & Li, 2016). Another paper focuses on the supplier selection process for after-sales service outsourcing. A simulation model provides a decision support system for a service buyer on specifying service categories, evaluation of service categories, and revenue sharing issues (Owida et al., 2016). A manufacturer's misinformation on product and service quality and its effect on profit expectation is analyzed from a retailer's perspective (B. Shen et al., 2018).

From a supplier's perspective, one paper solves spare parts inventory and supply network design simultaneously to find optimal values of an installed-base model (Jalil et al., 2011). Simulation models are used to help a service supplier on making decisions on spare parts levels, workforce mix, and asset allocation (Alabdulkarim et al., 2015) or capacity decisions (Chalal et al., 2015).

Game theoretical models solve the problems from both suppliers' and customers' perspective. These models mostly focus on contracting problems. For example, Liang et al. (2017) first attempt to find optimal contract parameters for a successful service level agreement. The model compares the lump-sum penalty and a linear penalty in the service contract. Then, the supplier's optimal behavior evaluated under the two different penalty mechanisms. Similarly, another model compares retail price maintenance, wholesale price contract, and franchise fee contract from the manufacturer's perspective and provides an optimal strategy for the retailer (Wenming Xie et al., 2014). Asymmetric service cost information is analyzed from both parties' perspectives for an after-sales service contract design (Lan et al., 2017) . One interesting model combines expected improvement in a product-service system from the supplier's viewpoint and the customer's viewpoint and attempts to maximize the sum of the improvements of the system (Pascual et al., 2017).

One possible research avenue in this category is three echelon supply chain algorithms with game-theoretical approaches. With the three-echelon supply chain modeling, research can be conducted on the manufacturer's viewpoint, the retailer's viewpoint, and the consumer's viewpoint in the same analysis. One recent example uses game theory to evaluate both parties' objective function. In addition to the manufacture's and retailer's objective function, the model considers customers' perceived service quality as well to investigate the outcomes of extended warranty service (He et al., 2018). Another potential research area is service offerings in online retail channels and omnichannel marketing. For example, Nault and Rahman (2019) look at a service offering problem in an online-to-online supply chain from the retailer's perspective. Their model posits that physical stores have an advantage over online stores as they can promote important after-sales services better than online stores. The model proposes strategies to mitigate the dis-utility cost of online-only stores. Future research can add service issues of online stores from a consumer perspective.

Level of Service/Service for Demand/Performance-Based Contracting

In this part of the categorization process, we analyzed the articles based on the service focus. First, we listed the papers which focus on the level of service provided by the supplier. Second, we analyzed the service model where the after-sales service is a variable in demand function. Finally, the papers in which performance-based contracting is the focus of analysis are promoted to the last category. Out of the 65 articles, 16 of them (24.6%) are related to performance-based contracting. From the remaining of them, 31 articles (47.7%) are about the level of services and 18 articles (27.7%) are about the services for demand.

In the after-sales service context, performance-based contracting can be defined as a strategy for optimizing service costs and improving the product performance of a capital good during its lifecycle (Randall et al., 2010). From a customer perspective, the customer cannot force a supplier on some decisions like capacity policy, effort level, etc. The customer, on the other hand, can provide a contractual mechanism to motivate suppliers in the desired direction. One model uses equipment downtime as a performance measure of a performance-based contractual agreement. This model analyzes a linear contract with a penalty rate depend on the equipment failure rate (Kim et al., 2010). Another model provides two new performance measurements that are calculated with a mean time between failures and mean time between replacement (Mirzahosseinian & Piplani, 2011). These equipment failures and the time between certain activities affect the availability of the product. On the availability calculation various numbers of parameters such as mean time to repair (Jin & Wang, 2012), fill rate (Liping Liang & Atkins, 2013), expected number of backorders (Lin et al., 2016) are utilized to solve performance-based contracting problems. Future research can focus on identifying multiple factors as a tool to use on performance measurement of an after-sales service contract.

In terms of service for demand, we analyzed the demand function of the models where the service is a variable. For example, D. Wu (2011) provides a linear function for product demand that depends on service efforts of retailers, service efforts of the manufacturer, and the retail price. In the model, service costs for both parties are calculated with a quadratic function as the cost of services increases non-linearly with service effort. One similar model incorporates sensitivity to the after-sales service offering for different customer segments (Kurata & Nam, 2013). In addition to based demand, retail price, and after-sales service level, Wenming Xie et al. (2014) add manufacturers' quality improvement effort as a new variable for demand function. Finally, one model compares the demand under two different retailers where one retailer is defined as a high level of service provides while the other defined as low-level (Roy et al., 2018). For future research opportunities, service level variables in a demand function can be increased based on the service type such as warranty, replacement, 7/24 support services, and so on.

We included different types of services in the level of service category. These types are including but not limited to repairs, inventory control, installed base management, capacity planning, and so on. In this part, first, we would like to give insights on installed-base management. Installed-base management can be defined as a marketing strategy where a manufacturer sells a product bundled with after-sales services like maintenance for a fixed usage or fixed time. One model in installed-base management attempts to find an optimal pricing strategy for effective installed-base management (Robotis et al., 2012). In terms of the level of repair services, one model adds the total cost of repair wait time to the objective function for an efficient repair network (Simmons, 2013). Capacity allocation is another issue in determining the level of service. One model tries to minimize the total cost of after-sales services which is a function of down-time cost, capacity policy cost, and inventory holding cost (Buyukkaramikli et al., 2015). One remark we need to make for this category is the need for identifying new variables that would have a direct effect on the level of services.

Distribution of Articles by Model Properties

In this class, we categorized articles according to their model properties. We focused on two properties for each model. First, we classified the articles based on the objective function. Then, we evaluated the numerical analysis of each article to identify what kind of data is used.

Profit Maximization/Cost Minimization

In this part, we take a look at the objective functions of the model and attempt to categorize them into profit maximization or cost minimization classes. Out of 65 articles, 37 of them (56.9%) of them solve a profit maximization problem while 25 of them (38.5) attempt to minimize the expected cost of after-sales services.

It may be straight forward to think that there would be no difference between minimizing cost and maximizing profit. For example, from the perspective of a supplier under a service contract where payment is fixed the maximum profit will only be achievable by minimizing the cost. In these cases, a model will get the same solution for both profit maximization and cost minimization objective functions. In the modern industry, however, contracts will be more complex, and profit will be a function of more than just the cost variable. Therefore, advanced models should consider both profit maximization and cost minimization in the problem solution. In this regard, we should point Jin and Wang's (2012) model where they formulated the problem as both profit maximization and life-cycle cost minimization.

Another remark we need to make is going beyond profit maximization and cost minimization. As a part of the corporate social responsibility initiative, the environmental effects of after-sales services minimized in one of the articles (Shokohyar et al., 2014) . Another model's objective function is maximizing the operational availability of a capital good while adding costs as a constraint to the model (Wei Xie et al., 2014) .

Finally, future research avenue is integrating profit maximization and cost minimization into a single function. One paper in product-service systems uses expected improvement scores and attempts to maximize it. Expected improvement is defined as cost reduction from the customer's perspective and profit increase from the supplier's perspective as a result of the product-service system. The model combines both improvements for the supplier and the customer in one objective function and aims to maximize the function (Pascual et al., 2017).

Real-Life Data/Parameter Estimation

One of the most effective ways to bridge a gap between practice and theory is the numerical experimentation of an analytical model. Using real-life data can improve moth model validity and reliability. Therefore, in this category, we classified articles based on numerical experimentation data. Out of the 65 articles, only 23 of them (35.4%) used real-life data on their numerical investigations. 42 of the articles (64.6%) used some estimated parameters to numerically solve their models.

The big data analysis and machine learning techniques can help researchers to define the distribution of demand or the distribution of failures for more accurate optimization models. On the other hand, data collection is a time and resource-consuming practice. To overcome this issue, one article used secondary data from existing research (Jin & Wang, 2012) . Providing the collected real-life data has helped researchers to improve the model and increase the body of knowledge in after-sales services. Some articles used both real-life data and computer-generated data since collecting all kinds of data is beyond the resource capacities (Alfian et al., 2014; Selçuk & Agrali, 2013) . Some other companies and industries that provided real-life data to the after-sales service research are Rich Europe(Bijvank et al., 2010) , IBM(Jalil et al., 2011) , ALFA(Visintin et al., 2014) , Sinoturk Jinan Fuqiang Power(Zhu et al., 2016), health care industry (Öner et al., 2010), semiconductor equipment industry (Mirzahosseinian et al., 2016).

One method for accurate parameter estimation is expert opinions and operation observations. For parameter estimations to be used in the numerical experiment, Pinçe et al. (2015) observed an after-sales service provider, collected expert opinions, and reviewed the existing literature and case studies. One caveat for expert opinion is that some managers may be biased on reporting their company performance (Daultani et al., 2019). One paper makes observations in defense and aerospace operations to approximate parameter estimation closest to a real-life scenario (Cohen et al., 2017) .

Collecting real-life data and using that data on the existing models is a possible research avenue for interested scholars. Real-life data will bring the theory and the practice closer and make theory more meaningful.

Remarks on Future Research

During the categorization process, many remarks for future research have been provided throughout our paper. After-sales services have various research avenues in topics like the number of products, functions used for calculations, the data type used in numerical experimentation, etc.

First, most of the models assume the scenario as a single-item, single-supplier one. Future research would improve those models by applying multi-item, multi-echelon criteria. Some researches specifically mention this issue in their discussion section. Some papers use multiple item cases in their models, but they assume that every single item has the same failure rate. In real life, each item or each part has a different failure rate. Using heterogonous failure rates rather than homogenous would improve the quality of the after-sales service models. In addition to the multiple items, multiple warehouses or multiple repair locations would better fit the real-life scenarios. The researchers use a single-item, single-echelon scenario for computational convenience. For more complex models, simulation tools can be utilized.

Secondly, most research on after-sales service applies liner demand function or linear cost function in their calculations. For example, Kurata & Nam (2010) uses a quadratic demand function; Kong et al. (2017) uses a linear function for demand estimation. A more robust model can use real-life demand data and machine learning techniques to find better demand functions that will minimize the error term on the model. In terms of after-sales cost, the research usually assumes a linear cost function. For example, (Robotis et al., 2012) assume that the cost of maintenance follows a linear function. In practice, however, the cost of maintenance increases as the life of the product increases. The future models need to address the cost of maintenance over time as a convex function. Moreover, in the case of multiple suppliers or multiple customers, there should be a different cost function for each supplier. By that, profit calculation for each party should have a unique function as well. From a product perspective, research should be conducted on differences in functions for a new product, for a used product, and remanufactured products. In terms of demand, finally, most articles use stationary demand. Future research can be done on non-stationary demand, stochastic demand, demand uncertainty, demand variability under different after-sales service levels.

Thirdly, most of the models have only one objective function for optimization. On the other hand, real-world operations have more than one objective to accomplish. The future models need to be modeled as a multi-objective optimization problem. Evolutionary multi-objective is one of the research areas that can be applied to after-sales services. For example, Altekin et al., (2017) mention that their model can be extended with multi-objective modeling as a combination of cost minimization and responsiveness maximization. The models can focus on different variables other than cost minimization and profit maximization. In the distribution of articles by model properties, we gave some examples of different objective functions found in the existing literature.

Fourthly, the new variable could be added to the existing models. Armistead (1991) posits that the success of after-sales support depends on fault freeness, safety, level of customer control, timing, and capability to recover from mistakes. Most of the existing models focus and timing and fault freeness. Future research could be done on safety issues, recovery, and level of customer control on after-sales services. In terms of multiple supplier scenarios, risk pooling, the reputation of the supplier, risk aversion, service competition would be good research opportunities. Another issue with after-sales services is monitoring the performance. For monitoring the performance, most models use availability or mean time between failures. More advanced models should include more variables on the repair process such as repairable inventories, the number of repair facilities, etc. For product-service systems, future research can add more cost variables based on environmental factors such as transportation cost, cost of reverse logistics, transportation time, and ease of maintenance. Also, in today's world, the life of the high technology products is getting shorter. Product obsolescence could be another variable that can be added to after-sales service models.

Finally, the existing research can be applied to real-life data. Empirical datasets can be used to confirm the validity of existing models. A researcher can compare the results of an analytical model with real-life scenarios. Empirical data would help researchers to define more accurate demand or failure distributions. In the literature, there is a need for estimating complete demand distribution and failure rate distribution with real data. Most models made some assumptions for computational efficiency. For example, service capacity assumed to be unlimited or contract duration generally normalized to one. Real-life data can help researchers to relax those assumptions. With empirical data, existing models could be applied to different industry settings.

Conclusion

Most of the analytical models in after-sales service management are discipline-specific and comparatively in a narrow domain. We inspected the existing mathematical models in after-sales services in this article. Then we attempted to categorize the mathematical models that study various after-sales service issues. We noted that there are manifold new problems and extensive groundwork for analytical models is needed. We tackled this gap and offered some possible future research avenues for analytical modeling and discussed a list of challenging new topics for prospective researchers. In conclusion, the literature suggests that it is important to obtain real-life data so that future research can attempt to address the complexity of product mix and failure rates. Current research is critical in developing the basic theory and the extension of that basic theory to real data will hasten the transition from basic research to practice.

ESSAY 2

MANAGING LIFE-CYCLE COST OF CAPITAL GOODS WITH AFTER-SALES SERVICE CONTRACTS: OPTIMIZATION OF SUPPLIER BEHAVIOR UNDER WARRANTY CONTRACTING

Introduction

In the last two decades, practitioners and researchers recognized that after-sales services have become an important source of revenue for capital goods suppliers. A McKinsey & Company report (2017) shows that after-sales services across 30 different industries constitute 25 percent of the average gross earnings margin while new product sales form only 10 percent of the margin. The same report shows that after-sales services would provide resources for 90 percent of the short-term growth of one of the original equipment manufacturers (OEM). Especially for capital goods manufacturers, after-sales services would have more impact on the profit margin of the firm. For example, almost half of the corporate profit for three big capital good supplier, Siemens, General Electric, and Honeywell International, comes from after-sales services (Govindarajan & Immelt, 2019).

As the impact of after-sales services on revenue streams is recognized, the companies pursue strategies to increase their gains from the after-sales services. On the flip side, after-sales services would account for a big part of the cost structure from a customer perspective. Life-cycle cost management becomes a more complex issue as the capital goods require more detailed analysis. Furthermore, the product life of capital goods is longer than the average consumer products. For example, engine systems used in aerospace, power plants, or heavy machinery used in manufacturing plants are more complex, have multiple parts that more prone to failures, and have a product-life span over 30 years. Although a capital good would require a high amount of investment in the initial phase of the product, the operating cost would exceed the purchase price of the product. For complex defense systems such as fighter jets or weapon systems, only 28 percent of the total life-cycle cost is purchasing price while 72 percent account for operating costs including after-sales service costs (Kim et al., 2017). After-sales services are one of the important parts of the operating cost of a capital good. For effective life-cycle cost management, a governance structure would help customers to control supplier behavior on after-sales services. One governance structure for after-sales services is warranty contracts.

The goal of a warranty contract is to shift the risk of failures from the customer to the supplier. Under a warranty contract, the supplier provides necessary after-sales services to maximize the availability of a capital good. With a warranty contract, the customer can provide an initial incentive to the supplier when the customer chooses to agree on warranty terms such as additional payments at the beginning of the contract. In return, the supplier can take a set of actions to meet the contract terms. To maximize the amount of profit in a warranty contract supplier can hold a spare parts inventory in different locations for quick reactions to failures, increase the product quality with investment in research and development, employ resources to inspection and repair activities, and outsource after-sales services to a third party service provider. In this article, we combine these activities into two categories: quality improvement efforts and spare parts inventory management. Based on these considerations, we attempt to answer the following research questions: 1) How do warranty contracts affect customers' life-cycle costs compared to the no-warranty scenario? 2) What is the effect of a warranty contract on suppliers' behavior? 3) What is the optimal set of actions for a supplier under a warranty contract?

We developed an analytical model to find answers to our research questions. Our analytical model is built upon two different categories of research. First, we define the after-sales service process and related maintenance and repair activities with the help of classical inventory management literature on spare parts allocation. Second, we employed a reliability investment variable that commonly used in performance-based contracting literature. With the help of performance-based contracting literature, we defined the new variable, quality improvement efforts of the supplier, to be used in warranty contracting scenarios. To analyze the relationship between the supplier and the customer, we compared two different scenarios: Purchasing a capital good without an after-sales service and purchasing it with a warranty contract. In the first scenario, the customer buys a capital good without an agreed-upon after-sales service. When a product failure occurs, the customers must compensate the supplier for resources used to fix the equipment. In the second scenario, the customer and the supplier agree on a warranty contract where the supplier provides necessary after-sales services without an additional fee. The goal of the supplier is maximizing the profit under both scenarios. The goal of the customer is the select the best scenario that minimizes the life-cycle cost of the product.

We used target availability as the main contract term in our model. As a contractual agreement, the supplier has to meet target availability. The supplier can provide target availability with two different applications: utilizing spare parts inventory or improving product quality. Therefore, we used spare parts inventory level and quality improvement effort as our decision variables. We employed the similar decision variables of the supplier that can be found on various after-sales service contracting literature (Kim et al., 2007; Öner et al., 2010; Selçuk & Agrali, 2013). We applied these decision variables in the context of warranty contracts. Our findings suggest that when the customer does not demand a certain warranty contract, the supplier would hold more spare-parts inventory and mean to sell more spare parts to maximize the earnings within a given target availability constrain. Under the warranty contract, however, the supplier would maximize the profit by decreasing spare parts inventory costs. In this case, the supplier could reduce the inventory and spare parts costs by improving product quality. In our study, we attempted to find the optimal decisions of the supplier on spare parts inventory and product quality investment under two different scenarios.

Our model shows that a warranty contract would help the customer to control the life-cycle cost of a capital good. Without a proper governing mechanism, an opportunistic supplier could increase the cost of after-sales services for the customer on life-cycle cost management. Although our findings are not new to scholars and practitioners, we contribute to the body of knowledge in many ways. First, we combine two decision variables, spare parts allocation, and quality improvement efforts, in an after-sales service model under a warranty contract. We provide optimal decision parameters for the supplier. Second, we compare optimal decision parameters under two different cases. Second, we provide a numerical example that we get the demand data from the aerospace industry. Our numerical experiment provides practical and managerial insights for after-sales service providers. Finally, our comparison of contractual scenarios enlightens the benefits of warranty contracts.

The remaining of the paper is organized into six sections. In the second section, we reviewed the relevant literature in spare parts inventory management and warranty contracting for after-sales services. In section three, we explain the service process and the model to be used in the analysis. In the fort section, we presented our analysis process. In the analysis section, we first provided the first best solution where the supplier and the customer act as an integrated firm. We solved the problem of a service contract without a warranty term. Then, we solved the model with the warranty contract. The fifth section provides a numerical example of the provided model. We used real-life demand data from a secondary source in the aerospace industry. Finally, we concluded our paper with a discussion section to provide managerial implications and future research directions.

Literature Review

The model we presented in this study built based on the METRIC model. The METRIC model provides s solution to spare part optimization problem (Sherbrooke, 1968). The METRIC model extended by various researches to multi-item, multi-echelon inventory management tools. In terms of after-sales service contracting, Kim et al. (2017) applied the

METRIC model to performance-based contracting and compared performance-based contracting with the resource-based contracting. Our research adopts the simplified version of the game-theoretical model provided by Kim et al. (2017) and contextualizes the model on a warranty contract. In addition to contextualizing the model on a new concept, we provide numerical experimentation to increase the ease of understanding the model.

In our model, warranty is a contract between the end customer and the supplier in the case where an obligation assigned to capital goods that requires the supplier to provide necessary after-sales services for the customer when the system fails to perform. The warranty has gained very high attention from the researchers. Fisk (1970) lists the good practices in warranty and states that the quality of a warranty can be defined under different factors including the quality of maintenance-repair services, product development, warranty contract completeness, and service level. Based on these suggestions, we combined the quality of maintenance-repair services with product development under quality improvement efforts. In our model, the decision variable "quality improvement efforts" can be defined as the effort provided by the supplier to improve product quality and maintenance-repair service quality. In addition to this decision variable, we look at the spare part inventory levels which has a direct effect on contractual requirement target availability.

Product quality or reliability is one of the most common research topics in warranty contracting. For example, Díaz, Fernández, and Márquez (2011) look at the quality and the contractual aspects of the warranty and give insights on best practices on warranty management. Reyniers and Tapiero (1995) focus on the manufacturer-supplier relationship and investigate the effect of contract parameters on product quality. The contract parameters on this research define the cost-sharing system between the manufacturer and the supplier. Their model is built upon an interesting conflict that comes from the issues of which party would bear the cost of manufacturing a premium quality product. Manufacturers would carry the cost of quality by implementing more inspections while the supplier would bear it by investing directly in quality improvement. The paper analyses this problem by employing a game-theoretical approach. One of the main findings of this research is as the supplier takes more share of the warranty cost, the product quality decreases. Similarly, Lim (2001) studies the manufacture-supplier relationship from the perspective of after-sales service contracts. The model compares to quality control mechanisms: price rebate for defective products and warranty contracts. The paper examines the trade-off between the two quality control mechanisms. The study finds that optimal contract parameters rely on the total cost of expected failures. Our context has a resemblance to these models, but our model also focuses on the spare-part inventory control aspect of warranty management. Balachander (2001) evaluates the signaling role of the warranty and the effect of signaling on the product quality. The author argues that there is an indirect relationship between the quality of the product and the warranty duration. Our research, however, counter argues that warranty would increase the quality efforts of the supplier. The main reason for the negative correlation on this relationship rests on the new entrant and incumbent competition.

Murthy (2006) provides a general literature review of the relationship between product quality and warranty. The paper shows that product quality and warranty cost is two closely related variables. In the discussion section, Murthy (2006) states that most of the analysis in warranty involves estimating the expected cost of the warranty, product quality, and reliability. Bai and Pham (2006) attempt to quantify warranty costs under a full-service warranty from the manufacturers' perspective. Hartman and Laksana (2009) aim to determine optimal warranty purchasing policies for consumers and optimal pricing strategies for the warranty provided. They calculate the cost warranty and show that offering a menu of warranty contract would be better than offering a single warranty contract. Samatlı-Paç and Taner (2009) present different repair strategies to control the cost of providing warranty service. The study shows that the performance of each repair strategy depends on product reliability, cost function, and the type of warranty contract. Dai, Zhou, and Xu (2012) develops a single-period, single-item model that examines the manufacturer-supplier relationship for warranty costing. Their model compares different cases where the manufacturer offers the warranty or supplier offers the warranty. When warranty duration is determined by the main warranty provider, the supply chain profit increases. The model is extended to analyze the effect of product quality on production cost and expected profit. Lu and Shang (2019) calculate the expected cost of warranty for pre-owned products for a third-party warranty provider and attempt to find optimal profit-sharing plan based on information sharing criteria. Main contribution of our research is that our model focuses on the supplier's decisions and tries to maximize the earnings of after-sales service provider rather than focusing on cost of warranty.

Most research on warranty focuses on the manufacturer-supplier relationship (Dai et al., 2012; Lim, 2001; Reyniers & Tapiero, 1995). For example, Balachandran and Radhakrishnan (2005) evaluate warranty issues on a manufacturer-supplier relationship and examine warranty/penalty contracts based on information sources such as inspections or reputation. The results show that a warranty contract that source the product information from inspection of incoming shipments would provide better outcomes. In the existing warranty literature, there is an opportunity to evaluate the concepts under different relationship structures. Esmaeili, Shamsi Gamchi, and Asgharizadeh (2014) fill this gap by exploring a three-echelon service contract between the manufacturer, the service provider, and the consumer. They attempt to solve three different objective functions for each party with the help of game theory. The model provides an optimal set of values including warranty price, sales price, and length of warranty for the manufacturer; maintenance cost, repair cost, and inspection cost for the service provider; and optimal service for maximum customer satisfaction. He et al. (2018) investigates a manufacturer-retailer relationship. They calculated the retail price when an extended warranty provided with the product. The authors discuss optimal service strategies for increased profit. Our research is different from the existing stream of warranty research in terms of relationship structure. Our paper evaluates a customer-supplier relationship where the supplier provides both product and the after-sales service.

The literature on the warranty studies various contracting scenarios. For example, Rahman and Chattopadhyay (2006) review strategies to effectively manage long-term warranties. They explain service contracts as one of the strategies. Similar to our findings, the paper suggests that for complex products such as capital goods service contract would be better. Our study quantifies and tests one of the findings of this paper. Mai, Liu, Morris, and Sun (2017) study the effect of extended warranties on store-brand products. They evaluate three different contractual strategies for extended warranties: fixed fee for the service, direct control of the manufacturer on the warranties, and cost-sharing. The manufacturer-direct contract is most similar to our warranty contract concept. Under this contract type, the manufacturer has the authority to decide on the price of the warranty, bear all the burden of warranty cost, and acquires all the profit from the warranty services. In our warranty contract, the supplier is responsible for all cost and profit of after-sales services. The study finds that the manufacturer-direct contract would accomplish the highest product quality improvement among other contracts.

There are various other topics studied in warranty contracts including but not limited to customers' perception about extended warranty offerings (Maronick, 2007) , firms' innovativeness and warranty costing (Mackelprang et al., 2015), and service leasing (X. Wang et al., 2019). Yeo and Yuan (2009) generate a model to find optimal maintenance and optimal level of repair based on the predefined cost function and the failure rate of the product. They investigate customers' preference for additional warranty. Our paper combines maintenance and level of repair quality with the product quality and assumes them as one variable. Examples of combining variables for computational convenience can be seen in warranty literature as well. For instance, Tong, Liu, Men, and Cao (2014) formulate a mathematical model to solve pricing and designing issues of extended two-dimensional warranty services. The model combines different maintenance strategies and adds usage rate to a warranty model. Similar to our model, Sundarraj (2006) focuses on decision parameters for different contractual scenarios including a warranty contract. The paper uses a heuristic algorithm to optimize the inventory for effective warranty service management. Our paper attempts to optimize the spare-parts inventory as well, but our model evaluates the relationship between inventory levels and quality improvement efforts. Also, our paper focuses on capital goods. One recent study estimates the life-cycle cost of complex business equipment based on initial cost and operating cost (Schlipf et al., 2019). Our study focuses on finding an optimal set of actions for the supplier under two different contractual scenarios.

In summary, we contribute the existing literature on after-sales service contract in two ways. First, we provide a new variable: quality improvement efforts, which affect both quality of product and after-sales service and analyze the trade-off between quality improvement efforts and spare-parts inventory level for complex capital goods. Second, we evaluate two contractual scenarios, time-and-material contract, and warranty contracts, and analyze their effectiveness on incentivizing optimal supplier behavior. From a practical perspective, our study provides insight into how warranty contracts can lead to increased quality improvement efforts by the supplier.

The Model

Table 2.1: Notations

Symbol	Description
λ	Product Failure Rate
MTBF	Mean Time Between Failures
ϱ	Quality improvement efforts

Symbol	Description
MTTR	Meant Time To Repair
l	Repair rate
N	Number of capital goods
s	Number of spare parts
O[ϱ]	On-order inventory
C_m	The total cost of unscheduled maintenance
H	Inventory on-hand
B	Number of backorders
A	Availability
f(x)	Probability density function
F(X)	Cumulative density function
L(x)	Loss function
z	z-score
$\mathrm{C_q}$	The total cost of quality improvement
$\mathrm{C_s}$	The total cost of spare parts
D_i	Total inconvenience cost
D_b	The total cost of backorders
k,t,n	Constants
m	Per unit unscheduled maintenance cost
h	Per unit cost of producing and holding spares
i	Inconvenience cost for each failure
b	The unit cost of backorder
T	Contract payment
$\mathrm{T_{nc}}$	Contract payment without warranty
$\mathrm{T_{cw}}$	Contract payment with warranty
$ϱ^*$, s^*	Optimal decision variables
ω	Lump-sum payment
α	Warranty coverage rate
C	Total cost for a single company
$ϱ^{FB}, s^{FB}$	Decision variables under the first best solution
E[ ]	Expected value
π	Profit
SC	Total supplier cost

Our model illustrates a supplier-customer relationship where the supplier sells a capital good and provides necessary after-sales services for the capital good. The customer purchases and operates N identical capital goods. The capital goods can fail on a random time and disrupt the operations. The supplier has two options to fix the operational disruption due to product failure: replacing or repairing the failed part. As an after-sales service provider, the supplier is responsible for stocking spare parts, repairing the failed part, and deciding on product quality. We assume that the contract duration is fixed and determined on the contract. Products fail at the rate of λ and the total number of product failures during the contract expected to be $E[\lambda]$. On average, it takes l amount of time to repair a failed part. We assume that repair time is fixed, and we quantified it as Mean Time To Repair (MTTR). We use Mean Time Between Failures (MTBF) and MTTR as a predictor of product and service quality. With the applicable investment, the supplier can reduce the MTBF by improving product quality and providing a better service with increased service speeds. MTBF can be found with the following equation:

$$MTBF = 1/\lambda \quad (1)$$

We define ϙ as the quality improvement efforts of the supplier. ϙ is a function of MTBF and MTTR. Therefore, the following equation provides the quality improvement efforts, which we will call quality efforts during the analysis process, of the supplier:

$$ϙ = 1/(MTBF * MTTR) = 1/(\lambda * l) \quad (2)$$

We need to note that there is a theoretical maximum level of quality efforts and the minimum level of quality efforts, which is the existing quality of the product. Thus, $\overline{ϙ} > ϙ > \underline{ϙ}$, the range of quality efforts will be between theoretical max and existing quality.

We assume that the customer has more power than the supplier. Accordingly, the customer offers a contract for the after-sales services, either pay for time and pars or warranty contract, which affects the supplier’s behavior on the quality efforts and spare-part inventory levels. In our model, we only focus on supplier behavior. Our model does not attempt to find the optimal contract parameters. For some examples that find optimal contract parameters on after-sales service contracting, we refer our reader to Kim et al. (2007) and Kim et al. (2017). When a part of a capital good fails, the supplier can change the failed part from the spare parts inventory, if available. The amount of spare part in the inventory is represented with s. The supplier produces the s number of spare parts after the contract is signed with the customer. The supplier also sells capital goods with N identical parts. In sum, the supplier will produce $N + s$ items before the contract. There will be $N + s$ items in the system where the supplier is responsible for maintaining and repairing the item. Therefore, we only examine a case where the supplier managed inventory, or Vendor Managed Inventory, system.

Repairs and Product Availability

We model the repair process according to the spare-part inventory management literature. We adopt the repair process and standard assumption provided on Kim et al. (2017). The occurrence of product failures follows the Poisson distribution. The service time is fixed and has a general distribution. We assume that there is only one repair server. Therefore, we model the repair process as an M/G/1 queue. If there is a spare part in the inventory, the supplier will replace the failed part with a working one. Alternatively, if there is no spare part to replace the failed unit, a backorder is recorded. On that account, we employ a one-for-one inventory policy on replacing the failed part, each defective unit goes into a repair facility.

We define $O[\varrho]$ as inventory on-order, which gives the number of parts that are in the repair process at a random time. $O[\varrho]$ has the mean of $1/\varrho$ and can be controlled by the supplier with the investment of quality improvements. O will have a direct effect on two important variables that will define our contractual constraints: H inventory on-hand and B, backorder number at a random point in time. B and H will be a function of spare parts level s and on-order inventory levels. The difference between initial spare part inventory levels and on-order inventory level will define the inventory on-hand number and the backorder level. If the on-order inventory level is greater than the initial spare part stocking, a backorder will occur. Therefore, we define backorder levels with the following equation:

$$E[B|\varrho, s] = \max\{O[\varrho] - s, 0\} \tag{3}$$

We measure the performance of the supplier with the target availability level. When there is a backorder, the availability level decreases. Based on that, we define the availability with the equation provided below:

$$E[A|\varrho, s] = 1 - \ E[B \mid \varrho, s]/N \tag{4}$$

Poisson distribution is the most common statistical parameter used to model failure rates in maintenance and repair literature. When the number of observations is large enough, Poisson distribution can be approximated with a normal distribution. Since we have N identical products that are large enough, we will use the normal distribution for the convenience of calculations. Based on the normal distribution, we can assume that the on-order inventory $O[\varrho]$ has the mean of $1/\varrho$ and the variance of $1/\varrho$. The probability density function of the normal distribution is as follows:

$$f(x) = \frac{1}{\sqrt{2\pi}} e^{\frac{-x^2}{2}} \tag{5}$$

Accordingly, the cumulative distribution function of the standard normal distribution is formulated as:

$$F(X) = \int_{-\infty}^{X} \frac{1}{\sqrt{2\pi}} \times e^{\frac{-x^2}{2}} \times dx \tag{6}$$

Based on the equations (5) and (6) we can get the loss function of the normal distribution as:

$$L(x) = f(x) \times x(1 - F(X)) \tag{7}$$

With the help of standard z-statistic formula, we can calculate the normal z score with the given quality level and spare parts inventory level with the following equation:

$$z \equiv \frac{s - E[O(\varrho)]}{\sqrt{Var[O(\varrho)]}} = \frac{s - (\frac{1}{\varrho})}{\sqrt{1/\varrho}} \tag{8}$$

Hence, the expected number of backorders can be quantified with the help of loss function. We calculated the expected number of backorders with the following equation:

$$E[B|s, \varrho] = L(z)/\sqrt{\varrho} \tag{9}$$

Cost Variables

In our model, we look at the costs from both the supplier's perspective and the customer's perspective. From a supplier perspective, three cost categories have a significant effect in our problem setting: (1) $C_q(\varrho)$, cost of effort for product quality improvement, (2) C_m, cost of unscheduled maintenance due to product failures, and (3) C_s, the cost of producing and stocking spare parts. From a customer perspective, we identified two costs related to the after-sales service of the product: (1) D_i, inconvenience cost due to unscheduled product failures and unscheduled maintenance, and (2) D_b, the cost of backorders due to business loss.

$C_q(\varrho)$ represents the resources spent to increase the product and service quality by the supplier. We calculate $C_q(\varrho)$ in terms of the dollar amount. We assume that the suppliers' quality improvement efforts will create a high cost and the cost function will be an exponential function. In real life, product quality can be improved to some point, but after a certain point, more investment will bring very little or no improvement. There, we hold the assumption that the limit of the cost function will be infinity. We calculated the cost of quality improvement efforts with the following function:

$$C_q(\varrho) = (\varrho k)^n - t \, , n > 3 \tag{10}$$

where the $k, t,$ and n represent constants for the cost function. When $n > 3$ we can get a function where $C_q{}'$, $C_q{}''$, $C_q{}'''$ is greater than 0.

The second cost generator for the supplier is unscheduled maintenance or repairs. When a part fails, the supplier needs to perform unscheduled maintenance for the customer. Assuming that each unscheduled maintenance cost represented by m, at a random time, the cost of unscheduled maintenance will be the product of failure rate and unscheduled maintenance. Thus, we can formulate the cost of unscheduled maintenance with the following equation.

$$C_m = \lambda \times m \tag{11}$$

Finally, for better after-sales services, the supplied needs to produce extra spare parts. Each part will have production costs and associated inventory costs. Let's assume that the sum of the production cost and inventory cost is equal to h. Then, we can represent the total cost for the spare parts, C_s, as:

$$C_s = s \times h \tag{12}$$

In addition to the supplier cost, we also formulated the customer's expected. We will use the customers' expected cost to find the first best solution to our problem setting. For the customer, there will be an inconvenience cost for each failure. Assuming that i is the inconvenience cost per failure, we calculate the cost of inconvenience for the customer with the following formula:

$$D_i = \lambda \times i \tag{13}$$

In addition to the inconvenience cost, each backorder will bring loss of business and opportunity cost to the customer. Based on business loss, the equation that represents backorder cost is as follows where b represents backorder cost per each backorder:

$$D_b = E[B|s, \varrho] \times b \tag{14}$$

Contracts

In our model, we compare two contractual cases where the customer offers a contract to the supplier. The contract specifies the payment amount that the customer pays to the suppliers. We represent the total payment amount with T. For our first contractual scenario, the customer signs a contract that makes the supplier responsible for necessary after-sales services. In this scenario, the supplier does not offer any warranty. Therefore, the customer has to make a payment to the supplier for every unscheduled maintenance due to product failures. We define the payment amount under no warranty scenario as T_{nc}. Once the customer offers the contract, the supplier selects the optimal decision values that represented by ϱ^* and s^*. The customer initially makes a ω amount lump sum payment to the supplier. Once the contract is finalized, the supplier selects the optimal decision values that represented by ϱ^* and s^*. Thus, we can calculate the expected payment amount to the supplier under no warranty scenario with the following equation:

$$E[T_{nc}|\varrho^*, s^*] = \omega + C_m \tag{15}$$

In the second scenario, the customer demands a warranty from the supplier. In this case, the supplier needs to cover α percent of the unscheduled maintenance as a part of the warranty. We define the payment amount warranty contract as T_{cw}. Once the customer offers the warranty contract, the supplier selects the optimal decision values as ϱ^* and s^*. Bakshi et al. (2015) define an after-sales service contract with α as the warranty coverage provided by the supplier. We adopted the same contract model in our warranty setting. The customer makes an initial payment of ω and compensates $(1 - \alpha)$ percent of the unscheduled maintenance cost to the supplier. Accordingly, the total amount of payment that will be made to the supplier can be calculated as:

$$E[T_{cw}|\varrho^*, s^*] = \omega + (1 - \alpha) \times C_m \tag{16}$$

In this study, we focus only on linear cost functions and linear payment functions. The payment functions and the cost functions will help us to define the supplier's problem with optimization.

The Supplier Behavior Analysis

In this section, we compare three optimization models. In the first subsection, we set the model to find the first best solution. Second, we find the maximum profit for the supplier under the pay-per-service contract. Third, we provide the optimal decision variables for warranty contracting. We compare the results with the first best solution to analyze which contractual scenario can best approximate to the first-best solution.

First-Best Solution

The first-best solution provides a benchmark for contract modeling. To provide a benchmark with a first-best solution, we assume that the supplier and the customer are an integrated single company. The goal of the company is minimizing the total cost, C, of after-sales services subjected to the target availability constrain, A_{min}. We define the problem of the company with the following objective function:

$$\text{Min}\, E[C|\varrho^{FB}, s^{FB}] = C_q + C_m + C_s + D_i + D_b \tag{17}$$

Subject to

$$E[A|\varrho^{FB}, s^{FB}] = A_{min} \tag{18}$$

$$\overline{\varrho} > \varrho^{FB} > \underline{\varrho} \tag{19}$$

where $E[C|\varrho^{FB}, s^{FB}]$ and $E[A|\varrho^{FB}, s^{FB}]$ are expected total cost and availability respectively with the given fist best optimal decision variables. The objective function with constraints provides us the optimal quality improvement effort and spare part stock levels when the two companies are integrated.

Profit Maximization on Time-and-Material Contract: No Warranty

In the case of no warranty, the supplier will be compensated by the customer based on the time and resources used for unscheduled maintenance. We assume that scheduled maintenance and other cost factors are included with the initial lump sum payment ω. Thus, the customer compensates the supplier with the cost of unscheduled maintenance C_m. The expected amount of contract payment under no warranty scenario will be equal to, as provided on the equation (15), $E[T_{nc}|\varrho^*, s^*] = \omega + C_m$. As a response to the contract, the supplier determines the optimal quality improvement effort and spare part stock levels ϱ^* and s^*. The decision optimal decision parameters maximize the supplier's profit. We formulated the objective function of the supplier as follows:

$$Max\, \pi|\varrho^*, s^* = E[T_{nc}|\varrho^*, s^*] - SC \tag{20}$$

Subject to

$$E[A|\varrho^*, s^*] = A_{min} \tag{21}$$

$$\overline{\varrho} > \varrho^* > \underline{\varrho} \tag{22}$$

where SC represents the total expenditures of the supplier for contractual purposes. The total expenditures for suppliers include the cost of producing spare parts, the cost of improving the quality, and the cost of unscheduled maintenance. The objective function is formulated to select to optimal ϱ^* and s^* such that the profit of the supplier is maximized. Constraint (21) guarantees that the target availability level is satisfied during the contractual agreement. Constraint (22) ensures that the quality improvement efforts are between the theoretical maximum quality level and the existing quality level.

Profit Maximization Under Warranty

When the contract provides a warranty, the supplier takes responsibility to cover a share of the unscheduled maintenance cost. First, we defined α as the customer's share on unscheduled maintenance costs. Although regular warranty on consumer products covers all the costs for an unexpected product failure, warranty for complex goods may fail to cover all costs of product failures. In the case of capital goods, the supplier can only cover a certain part of the product failure. The customer will encounter some cost factors that cannot be covered by the warranty. Therefore, we assume that the customer will compensate the supplier for $1 - \alpha$ portion of the unscheduled maintenance cost. We assume that α is the ex-ante part of the contract. The customer can negotiate with the supplier on the rate of cost-sharing. We provided the expected amount of payment under a warranty contract on the equation (16). The payment from the customer to the after-sales service provider will be equal to $[T_{cw}|\varrho^*, s^*] = \omega + (1-\alpha) \times C_m$. As a response to the contract terms, the supplier chooses optimal decision variables ϱ^* and s^*. With the optimal quality improvement effort and spare part stock levels, the supplier attempts to maximize the profit. The following objective function formulates the supplier's problem under a warranty contract.

$$Max\ \pi|\varrho^*, s^* = E[T_{cw}|\varrho^*, s^*] - SC \tag{23}$$

Subject to

$$E[A|\varrho^*, s^*] = A_{min} \tag{24}$$

$$\overline{\varrho} > \varrho^* > \underline{\varrho} \tag{25}$$

where SC represents the total expenditures of the supplier regarding after-sales services during the contract horizon. Cost of improving quality, cost of producing spare parts, and cost of unscheduled maintenance are cost factors for the total expenditures of the supplier. With the profit maximization, the supplier selects the optimal decision parameters that satisfy contains. Constraint (24) represents target availability. Constrain (25) provides theoretical bounds of the quality improvement efforts.

Solutions Algorithms

All the objective functions in our model have non-linear components. The appropriate solution algorithm would be a goal programming model. Since our model involves non-linear functions, our problem is difficult to solve due to the complex nature of non-linear models combined with integer programming (O. K. Gupta & Ravindran, 1985; Jin & Wang, 2012). Existing algorithms on non-linear programming take a step by step solution approach. Successive solutions are found first, then the solutions branched out to find an integer solution. Recently, heuristic approaches and genetic algorithms have been extensively used to find the optimal or second-best solution to non-linear goal programming models with complex objective functions (Jin & Wang, 2012; Nowicki et al., 2008; Uvet et al., 2019).

As our objective functions constructed with only two decision variables ϱ and s, we can solve the problems with the iteration method and provide the optimal solution. We applied the following solution procedure which is similar to Jin & Wang (2012): First, we assume that there is no spare part in the inventory, $s = 0$. While $s = 0$, we assume that quality improvement effort is equal to theoretical minimum, $\varrho = \underline{\varrho}$. Then, we let the ϱ increase from $\underline{\varrho}$ to theoretical maximum $\overline{\varrho}$ in a very small quantity and compute the objective functions. After each adjustment of ϱ, we added 1 to the s. We increased the number of spare parts until s reaches a level that can be observed in the existing literature. If the objective function is greater than the previous iteration, we select the current ϱ and s values. If there is no improvement in the profit function, we stop iterating over changing the decision variables.

Numerical Example

We collected the data for our numerical example from the existing literature on after-sales contracting. Using the existing literature for numerical experimentation is a common practice in after-sales service literature. For example, Jin and Wang (2012) work with the cost data provided on Kim et al. (2007), Bakshi et al. (2015) draw the parameter values for numerical study from various existing papers. Under this trend, we used the cost data from Bakshi et al. (2015). Our numerical example provides optimal resource allocation by investing either on spares or quality improvement while maximizing the supplier's profit within a given availability target.

In our example, the service provider contracted to manufacture and supply complex avionic systems to the customer. Table 2.2 provides the necessary parameter values to conduct the optimization analysis for objective functions provided on the equations (17), (20), and (22). We assume that the cost of the backorder is *b = $2,000,000* per each backorder that occurred during the contract horizon. The theoretical minimum for quality improvement effort is equal to $\underline{\varrho} = 1/N$. The number of airplanes in the system is N = *150*. The parameter value for the maximum quality improvement effort is $\overline{\varrho} = 0.1$. Per unit cost of producing and holding spares is h = *$70,000*. The inconvenience cost for each failure is i = *$175,000.* An unscheduled maintenance cost per failure is m = *$800,000*. The cost values are selected based on the research provided on Bakshi et al. (2015). We further make assumptions on the contract parameters. First, we assume that the initial lump-sum payment amount to the supplier is ω = *$10,000,000.* All other parameters are explained in the model section. We run our algorithm to analyze three scenarios including the first best solution to find the best decision parameters ϱ and s such that maximizes the profit of the supplier. Another variable that defines our constrains on the models is the target variable A_{min} is further analyzed with sensitivity analysis. We further assume that constant values are $k = 1{,}000$, $t = 10{,}000$, and $n = 4$. Finally, the warranty coverage rate is $\alpha = 0.5$.

Table 2.2: Parameters for the Numerical Study

Parameter	*Value*	*Parameter*	*Value*
b	$2,000,000	ω	$10,000,000
N	150	k	1,000
h	$70,000	t	10,000
i	$175,000	n	4
m	$800,000	α	0.5
l	3	A_{min}	0.95

Table 2.3 outlines the optimal values for ϱ and s under the first-best solution, under each different scenario. Based on the optimal values, we can first conclude that there is an inverse relationship between ϱ and s. While no contract scenario provides a higher value for s, the warranty contract requires higher improvement on the quality ϱ, which provides the second-best solution. We need to note that the supplier has little or no interest in investing in product quality improvement efforts under time and materials contracts. Even if we increase the target availability, the supplier is just incentivized to increase the spare part inventory level. On the

other hand, the supplier is better off with increase quality improvement efforts when the warranty contract requires a higher level of target availability. Figure 2.1 depicts the relationship between the ϱ and s under different contract scenarios.

Table 2.3: Optimal Decision Variables and Total Cost, $A_{min} = 0.95$

Parameter	*First best*	*No warranty*	*Warranty*
ϱ	$2,416,198	$643,319	$1,550,765
s	18	28	21
SC	$10,432,938	$11,982,986	$10,565,333
π	-	$7,396,681	$3,206,951
TC	$26,911,170	$29,034,774	$27,215,678

Our optimal decision parameters show that the warranty contract comes closest to the first-best solution, hence provides the second-best solution. The profit π values show that the supplier may exploit the contract to increase the profit by providing more spare parts and reduced product quality.

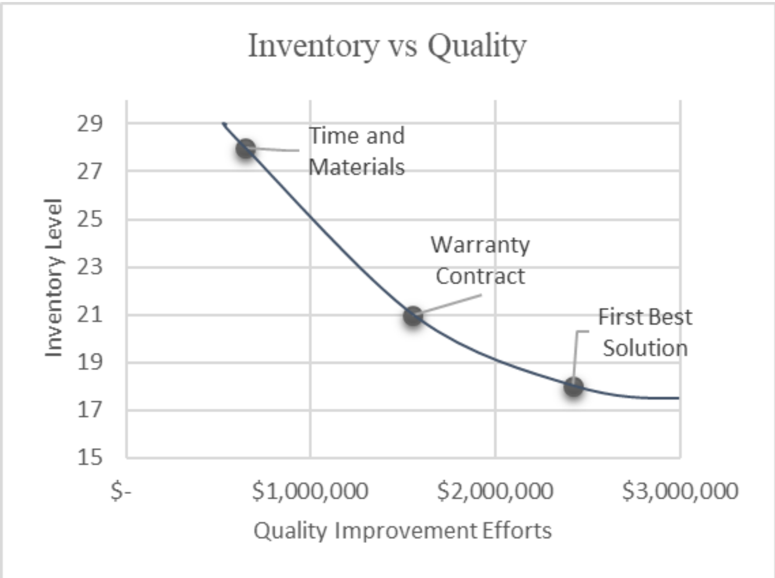

Figure 2.1: Spare parts inventory level vs quality improvement efforts

We further analyzed the effect of target availably constrain on the optimal decision variables. In our model, we first set the target availability constrain $A_{min} = .90$. We run the model for both contractual scenarios and investigated the result of our numerical experimentation. We change the value of target availability to .95 and .99 and investigated the optimal decision variables. We need to make a note that as the availability increases, the total cost of the contract (TC) decreases. On the other hand, the highest quality improvement effort is observed when the target availability set to $A_{min} = .95$ for the warranty contract. Our finding is consistent with the findings on the existing literature on contracting after-sales services (Jin & Wang, 2012). Table 2.4 presents the optimal decision parameters and profit level under different target availability levels.

Table 2.4: Optimal Decision Variables under Different Target Availability Levels

Parameters	$A_{min} = .90$		$A_{min} = .95$		$A_{min} = .99$	
	T&M	***Warranty***	***T&M***	***Warranty***	***T&M***	***Warranty***
ϱ	$586,168	$1,404,685	$643,319	$1,550,765	$655,203	$1,487,582
s	21	14	28	21	37	30
π	$7,943,832	$3,749,209	$7,396,681	$3,206,951	$655,240	$2,600,961
TC	$43,752,461	$41,808,535	$29,034,774	$27,215,678	$17,625,280	$15,878,236

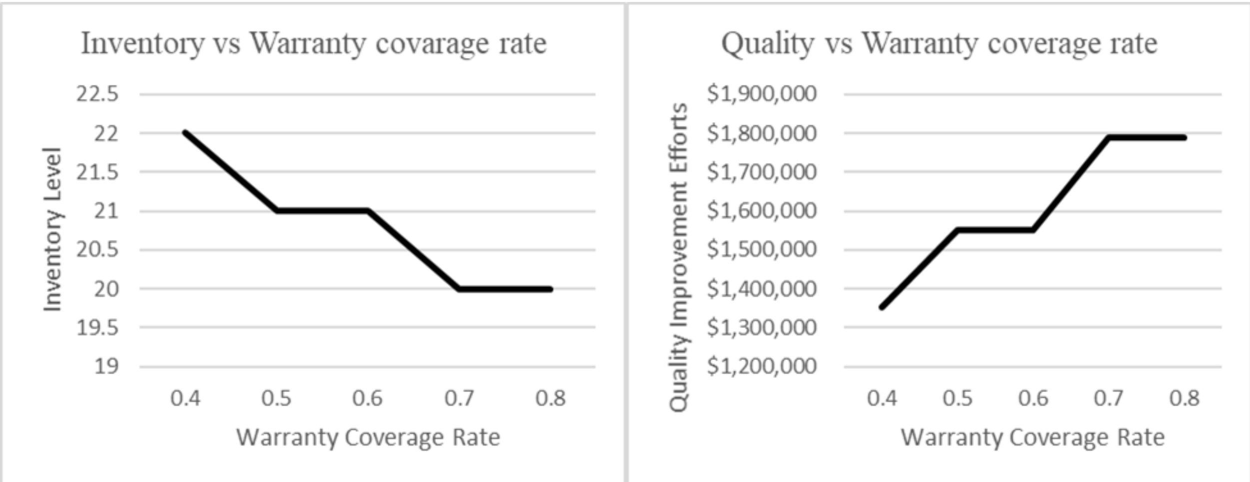

Figure 2.2: Optimal decision variables under different warranty coverage rates

As a final step of the numerical experimentation, we investigated the effect of warranty coverage rate α on the decision variables. Recall that on a warranty contract, the supplier needs to cover α percent of the unscheduled maintenance as a part of the warranty. The customer compensates (1-α) percent of the unscheduled maintenance cost to the supplier. Figure 2.2 illustrates the relationship between the warranty coverage rate and the optimal decision variables. The results of the numerical experiments show that as the warranty coverage rate increases the supplier should put more effort into improving the product quality.

Conclusion

Using optimization models with generic algorithms and heuristic approach, we study the optimal spare parts inventory and product quality improvement effort decisions on after-sales service contracting for a complex capital good. We mainly focused on a warranty contract -a contract where the supplier is responsible for a certain portion of the product failures- and compared it to time and materials contract with no warranty. The warranty contract in our model is designed to protect the buyer from the opportunistic behavior of the supplier by better incentivizing the supplier with governing structures. Although there is various research on warranty, our paper sheds light on how to implement a warranty contract for the after-sales services for multiple capital goods and challenges in warranty contracts, namely product improvement efforts and spare parts inventory management.

Our analysis proposes that time and material contract is not as efficient as a warranty contract in providing incentives to the supplier to improve product quality. Without a proper warranty mechanism, the supplier prefers to meet the target availability level by building larger spare parts inventories at the expense of improving the product quality. Under warranty contract, however, the supplier maximizes her profit by both increasing the product quality efforts and spare parts level while achieving the target availability requirement. Compared to the first-best solution, where both the customer and the supplier are assumed to be the part of a single company, both contractual scenarios prompt some inefficiencies such as less effort on product quality and increased spare parts inventory spending. When we compare warranty contract to time and materials contract, on the other hand, a warranty contract provides a better outcome that is closer to the first-best solution.

Furthermore, we find that the successful application of a warranty contract for the highest product quality depends on selecting the right target availability level and warranty coverage rate. First, our analysis shows that the supplier provides a higher effort on certain target availability levels. Although increasing the target availability level reduces the total cost of the contractual relationship, the supplier achieves this by increasing the spare parts inventory level. As a result, the supplier's expected profit decreases as the customer demands higher target availability levels. In this case, the supplier may refrain from entering the contractual relationship. The customer should discuss with the supplier before finalizing the contract on the target availability level. Second, the warranty coverage rate has a significant effect on decision variables. Our numerical experimentation shows that as the warranty coverage rate increases, the supplier is more incentivized to invest in product quality improvement while reducing the spare part inventory level. The higher warranty coverage rate brings the warranty contract model closer to the first-best solution. On the other hand, a high warranty coverage rate decreases the supplier's expected profit significantly. Thus, the supplier may lose interest in singing an after-sales service with the customer. Negotiation skills of both the customer and the supplier play a crucial role in determining the warranty coverage rate on the contract horizon.

Finally, we predict that the warranty contract results in higher quality improvement efforts, lower spare part inventory, and decreased total contract cost. However, the gap between the warranty contract and the first-best solution provides future research ideas. In a follow-up study, we plan to compare different governing mechanisms to warranty contracting to close the gap between the first-best solution and warranty contract. As our model comes with various assumptions, future research can relax the existing assumptions to improve the model validity. More empirical data collected from real cases would provide more to our understanding of the after-sales service contracting theory.

ESSAY 3

EXCEEDING THE EXPECTATIONS ON AFTER-SALES SERVICES: ANALYSIS OF PERFORMANCE-BASED CONTRACTS COMPARED TO WARRANTY CONTRACTS

Introduction

The demand for capital goods is very volatile and unpredictable. To alleviate the volatile revenue stream due to uncertain demand, manufacturers are pursuing innovative alternatives to increase revenue channels. One of the alternatives for capital goods manufacturers is after-sales services. In today's competitive environment, after-sales services have become a key source of profit lever, competitive advantage, and growth (Chowdhry, 2018). The industrial reports show that the market for after-sales services is large and continuously growing. In some capital goods manufacturing industries, after-sales services contribute to as high as 55 percent of the revenue (Ramaswamy et al., 2017). After-sales services across various industries incorporate 25 of the gross earnings margin on average. Product sales, on the other hand, constitute only 10 percent of gross earnings margin on average. Moreover, after-sales services are the main source of short-term growth investment for one company in the capital goods manufacturing industry (Ambadipudi et al., 2017). For capital goods manufacturers like Siemens, General Electric, and Honeywell International, almost half of the profit comes from after-sales services(Govindarajan & Immelt, 2019).

As the companies realize that after-sales services have a greater profit margin than selling goods, the after-sales service providers craft strategies to increase the profit margin. On the other hand, the pursuit of increasing after-sales service profit of suppliers results often leads to expanded costs for customers. For complex capital good systems such as weapon systems, airplanes, manufacturing equipment, after-sales and operating cost comprise a higher percentage of product life-cycle cost. For example, for a fighter jet, while only 28 percent of the life-cycle cost comes from purchasing the fighter jet, 72 percent of the total life-cycle cost is composed of operating and after-sales service costs (Kim et al., 2017). Moreover, the cost of after-sales service continues to increase for fighter jets. According to the Government Accountability Office September 2018 report, the maintenance costs for F-22 Raptor fighter jet increased by almost $255 million from 2011 to the fiscal year 2016. The report indicates that the main reason for the increase in maintenance cost is the service providers. Life-cycle cost management for capital goods remains as a complex issue and requires further analysis despite the theoretical advancements on the subject matter since 2011. For capital good buyers, one avenue to reduce life-cycle cost is the effective management of after-sales services. Governance structures and the contract provides the necessary tool for effective after-sales service cost management.

Performance-based contracts and warranty contracts are some of the remedies that govern the life-cycle cost of capital goods. The goal of both performance-based contracting and warranty contracting shifts the responsibility for unexpected product failures from the customer to the supplier. The essential idea behind the warranty contracting for capital goods is assuring product availability by providing necessary after-sales service at no cost or discounted rate. Performance-based contracting, however, is a novel approach that changes ownership structure, redefines maintenance-repair responsibilities, and ties payment to availability (Hypko et al., 2010a; Lay et al., 2009). Under a performance-based contract, the supplier is responsible for all maintenance, ownership, and in some cases even the operation of the product. Moreover, the supplier is only compensated based on the realized output and performance of the product. Therefore, to augment the income from the contractual relationship, the supplier needs to provide maximum product availability and reduce the number of product failures by offering premium product quality. In this study, we analyze the product quality improvement efforts, along with spare parts inventory decisions, of the after-sales service provider under a performance-based contract. Specifically, we compare the supplier decision under a warranty contract and a performance-based contract. Therefore, we attempt to provide answers to the following three research questions: 1) How does performance-based contracting to affect the life-cycle cost of a capital good compared to warranty contracting? 2) What is the effect of performance-based contracting on the after-sales service provider? 3) What is the optimal set of actions for the after-sales service provider under a performance-based contract?

We developed an optimization model to answer the research questions. Our optimization model is built upon existing research on performance-based contracting. First, we characterize an after-sales service system and associated repair and maintenance operations based on classical inventory management literature on spare parts provisioning. Second, we adopt the reliability investment variable from existing performance-based contracting as quality improvement efforts of the supplier. We built our model to analyze and compare warranty contracting and the performance-based contracting relationship between a customer and a supplier of a capital good. Our comparisons involve three different scenarios: the first-best solution where the customer and the supplier are a subsidiary of a parent company, purchasing a capital good with an additional warranty, and purchasing only outcomes rather than the product. In the first scenario, the parent company decides to minimize the total cost of after-sales services. For the second scenario, the supplier offers additional repair and maintenance service bundled with the product. In the third scenario, the supplier is only compensated based on the realized performance of the product. Under each scenario, the supplier decides on the spare-part inventory level and the quality improvement efforts. The goal of the supplier is maximizing the profit while the goal of the customer is the find the second-best option where the total cost of the contract is minimized.

Target availability is used as the main binding factor of the contractual agreement in our model. As a contractual agreement, the customer defines a maximum target availability level that will affect the payment amount to the supplier. The supplier is required to meet the desired availability level. The supplier has two means to control the availability level: investing in spare-part provisioning or investing in product quality improvements. The spare-part inventory level and reliability investment decision is heavily investigated on the performance-based contracting literature (Guajardo et al., 2012; Mirzahosseinian & Piplani, 2011; Öner et al., 2010; Selçuk & Agrali, 2013) . We adopted a similar set of decision variables to compare performance-based contracting to warranty contracting. As our previous study indicates that the warranty contract incentivizes the supplier to invest more in product quality improvement efforts rather than stocking more spare parts to meet contractual requirements. However, that study shows that there is a big gap between the first-best solution and the warranty contract. Our model demonstrates that the performance-based contracting curtails the gap between the optimal decision variables and the first-best solution parameters. Under the performance-based contracting, the supplier is better off with increasing the investment in quality improvement efforts. Comparing the warranty contract, the performance-based contracting produce improved result on increasing product quality and reducing total contract cost.

Our numerical experimentation reveals that performance-based contracting is an effective tool to control the cost of the product lifecycle. Even with a governing mechanism like warranty contracting, the supplier does not provide maximum product quality achievable for enhanced life-cycle cost management. Although our finding is not novel to the existing literature and business practices, our contribution to the body of knowledge is manifold. First, we connect two decision variables -quality improvement efforts and spare-part provisioning- in an after-sales service model under a performance-based contracting. Second, we compare the optimal values for the decision variables under warranty contracting and performance-based contracting. Third, we provide numerical experimentation with the secondary data from existing literature on performance-based contracting on the aerospace industry. Our numerical experimentation yields worthwhile managerial and practical insight for customers, manufacturers, and after-sales service providers of capital goods. Finally, our comparison models shed light on the benefits of performance-based contracting.

The rest of the article is organized under six sections. The second section presents a literature review on performance-based contracting for after-sales services. Section three introduces the after-sales service process and the model assumptions used in the formulation of the process. The analytical model with objective functions and constrains is demonstrated in the fourth section. In the analysis section, we first presented the first-best solution where the supplier and the customer are a subsidiary of a parent company. Then, we attempted to find the optimal decision parameters under warranty contracting and performance-based contracting. In section five, we performed numerical experimentation with data obtained from the literature on performance-based contracting in the aerospace industry. Finally, we complete our study with a discussion section to provide future research avenues along with practical and managerial implications.

Literature Review

Performance-based contracting refers to contracting on specific goals or performance outcomes rather than buying a good or service. Performance-based contracts tie payment options to the realized output of the after-sales service provider. Performance-based contracting gained increased attention during the last three decades across the different disciplines. Performance-based contracting research can be observed in healthcare management (Jiang et al., 2012; Y. Shen, 2003), public administration (Heinrich & Choi, 2007), in human resources management as performance-based fee contracts (Grinblatt & Titman, 1989), in collaborative services (Roels et al., 2010), marketing (Chennamaneni & Desiraju, 2011; Dellarocas, 2012), and in supply chain management as performance-based logistics (Randall et al., 2010). As the nature of after-sales services for capital goods falls under supply chain management, our literature review focuses on the concept of performance-based logistics. We will use performance-based contracting, outcome-based contracting, or performance-based contracting interchangeably.

The literature on performance-based contracting employs a variety of research methods including but not limited to case studies, surveys, qualitative research, literature review, and analytical modeling. Early research on performance-based contracting case studies focuses on public bus services (Hensher & Stanley, 2003), railway industry (Fearnley et al., 2004), highway maintenance (Anastasopoulos et al., 2010), and defense industry (Datta & Roy, 2011; Kleemann et al., 2012). Ng and Nudurupati (2010) attempt to diagnose risks and barriers to implementing outcome-based contracting practices and provide remedies for those barriers including uncertainty, dependency, and cultural change. Lazzarotto et al. (2014) analyze nine different performance-based contracts to emphasize the importance of performance evaluation and supplier selection process. Hensher and Stanley (2003) evaluate different performance-based contracting practices in bus and train services and provide desired contract terms including the scope of the contract, duration, fleet size, allocation of risk among parties, incentives, responsibilities, quality, and asset ownership. Our research is built upon some of those contract terms such as incentive types, risk allocation, and quality in a comparative analytical model. Ng et al. (2009) conduct another case study for outcome-based contracting practices in the defense industry. Their research concludes that the effectiveness of an outcome-based contract requires a co-creating of value rather than a focus on individual value creation. Based on their finding, we built out the first-best solution scenario where the co-creation is enforced by a parent company. Then we compare our contractual scenarios to the fist-best solution.

Another research methodology stream in performance-based contracting is qualitative approaches. In a comprehensive qualitative study with expert interviews, Randall et al. (2010)

introduce a theoretical framework for performance-based logistics by utilizing the grounded theory. The research incorporates performance-based logistics to service-dominant logic and suggests collaboration activities, organizational culture, information systems, and external factors as potential predictors of effective performance-based contracting. Guo and Ng (2011) interview practitioners and observe performance-based contracting practices. They argue that co-value creating under performance-based contracting is dependent on personal relationships and cooperation instead of legal bindings. A qualitative study by Sols and Johannesen (2013) introduces three different performance-based logistics practices based on risk allocation, supply resiliency, and cost control. Randall et al. (2015) interview performance-based logistics practitioners in the defense industry and identify team level success criteria for performance-based contract management. In addition to a comprehensive literature survey, Sols et al. (2007) conduct interviews with industry experts to provide a contractual framework for performance-based logistics. The findings of their study suggest that the purpose of a contract, incentives, and willingness to enter contract relationships are three main elements of the contract framework. We build our model based on the three elements. Our performance-based contract model provides a reward/penalty structure, a purpose as availability, and willingness as a different set of constraints.

A systematic literature review is abundant in the topic of performance-based contracting. Selviaridis and Wynstra (2015) provide the most comprehensive literature review in performance-based contracting. Glas et al. (2018) revise 102 scientific articles on performance-based contracting to discuss the lack of performance management practices such as data collection, strategic alignment, and data analysis in the existing literature. Our numerical experiment attempts to fill this gap by collecting data from secondary sources. Hypko et al. (2010b) provide an extensive literature review on performance-based contracting practices. Their research makes recommendations on best practices of performance-based contracting and ownership structure for capital goods manufacturers and service providers. In a follow-up study, Hypko et al. (2010a) reveal that, despite increased uncertainty, performance-based contracting would increase the innovativeness, quality, profit, and customer loyalty for capital goods manufacturers. Our numerical experiment attempts to validate the proposition on quality revealed in this study. Holmbom et al. (2014) argue that contract design, performance metrics, and payment structures are key aspects of a successful performance-based logistic application. Similarly, our model compares two different scenarios to emphasize the importance of payment structures.

The limited number of research papers with a survey design focus on various aspects of performance-based contracting. Hünerberg and Hüttmann (2003) attempt to measure suppliers' and customers' perspectives on performance-based pricing strategy in the capital goods manufacturing industry. Similarly, our focus is on the capital goods industry. Randall et al. (2011) survey 61 practitioners of performance-based logistics to show that relationship structure, organizational culture, and business type are significant predictors of an effective performance-based contract. In a follow-up study, Randall et al. (2015) present performance-based logistics as an application of service-dominant logic in a supply chain management concept. MacCormack and Mishra (2015) argue that the performance-based contract is not different from time and material contracts in terms of the impact on product quality. We counter-argue that performance-based contract improves the product quality. Our model shows that investment in product quality increases under performance-based contracting. We should note that our model compares performance-based contracting to warranty contracting.

Our paper presents an analytical model to compare different contracting scenarios. Our model utilizes the METRIC model which provides solutions to a spare-part inventory optimization problem (Sherbrooke, 1968). In terms of performance-based contracting, Kim et al. (2017) provide an application of the METRIC model in the buyer-supplier relationship. Our research simplifies the model presented by Kim et al. (2017) and contextualizes the model to compare performance-based contracts with a warranty contract. Moreover, we provide numerical experimentation to increase the tractability of the model along with conceptualizing in a different setting.

In our model, we provide three optimization models to compare the effectiveness of the warranty contract and performance-based contract. In both contract scenarios, the supplier is responsible to ensure product availability by providing necessary after-sales services for the customer to prevent product failures. The supplier has two tools to ensure product availability: quality improvement and spare-part provisioning.

There exists plenty amount of papers on reliability improvement efforts and spare-parts provisioning in the existing literature of performance-based contracting. Guajardo et al. (2012) compare the effect of performance-based contracting and time and materials contracting on product reliability based on real-life data from the aerospace industry. Jin and Tian (2012) analyze the tradeoff between spare-parts inventory levels and reliability investments in various scenarios with a varying number of products to service. Settanni et al. (2016) provide strategies to utilize existing reliability data on the design of performance-based contracts. Kim et al. (2017) build a game-theoretical model to analyze reliability, spare parts inventory, and asset ownership issues under resource-based contracts and performance-based contracts. Jin and Wang (2012) use the inherent failure rate as a reliability indicator and incorporates it to their analytical model along with spare-parts level, repair duration, usage rate, and the number of products to minimize the life-cycle cost of the product under performance-based contracting. Öner et al. (2010) categorize reliability cost into production cost, design cost, failure cost, and maintenance cost to optimize reliability cost and inventory cost for life-cycle cost management of capital goods. Wang et al., (2020) propose a reliability model to maximize the profit rate of the supplier based on different failure functions under a performance-based contract. Xie et al.

(2014) attempt to optimize product availability with redundancy allocation and spares stocking decisions. Bakshi et al. (2015) examine the effect of performance-based contracting on product reliability signaling in contrast to resource-based contracting. Mirzahosseinian and Piplani (2011) present an advanced inventory optimization model that examines repair rate, inventory level, failure rate, and the number of service providers for systems under performance-based logistics. Nowicki et al. (2008) optimize the spare-parts level for multi-item and multi-tier performance-based logistics context to maximize supplier profit. Our study utilizes the existing literature on spare-part provisioning and reliability under performance-based contracting and blends it with quality improvement effort to compare the effectiveness of performance-based contracting to warranty contracting.

In summary, our contribution to the existing literature on performance-based contracting is two folds. First, we introduce quality improvement efforts which result in improved product quality and after-sales service and analyze the trade-off between quality improvement efforts and spare-part provisioning efforts in the capital goods industry. Second, we examine performance-based contracting in contract to warranty contracting in terms of the effectiveness of the contracts on motivating suppliers to invest more in product quality. From a managerial perspective, our study shed lights into how performance-based contract can lead to more increased quality improvement effort by the supplier.

The Model

Table 3.1: Notations

Symbol	Description
λ	Product Failure Rate
MTBF	Mean Time Between Failures
ϱ	Quality improvement efforts
MTTR	Meant Time To Repair
l	Repair rate
N	Number of capital goods

Symbol	Description
s	Number of spare parts
$O[\varrho]$	On-order inventory
C_m	The total cost of unscheduled maintenance
H	Inventory on-hand
B	Number of backorders
A	Availability
$f(x)$	Probability density function
$F(X)$	Cumulative density function
$L(x)$	Loss function
z	z-score
C_q	The total cost of quality improvement
C_s	The total cost of spare parts
D_i	Total inconvenience cost
D_b	The total cost of backorders
k,t,n	Constants
m	Per unit unscheduled maintenance cost
h	Per unit cost of producing and holding spares
i	Inconvenience cost for each failure
b	The unit cost of backorder
T	Contract payment
T_w	Contract payment for the warranty contract
T_p	Contract payment for the performance-based contract
ϱ^*, s^*	Optimal decision variables
ω	Lump-sum payment for warranty contract
ρ	Lump-sum payment for performance-based contract
α	Warranty coverage rate
ν	Penalty rate for availability
C	Total cost for a single company
ϱ^{FB}, s^{FB}	Decision variables under the first best solution
$E[\ ]$	Expected value
π	Profit
SC	Total supplier cost

The model is constructed to illustrate supplier-customer transactions where the supplier provides a capital good and necessary after-sales services for the product. The customer purchases or operates N amount of single type capital good. Random failure of the product disrupts the operations of the customer. The supplier is responsible to fix the product by either replacing or repairing the failed product. As a seller and after-sales service provider, the supplier has control over the stoking levels of spare parts, product quality, and repair activities. The supplier provides after-sales services to the customer on a fixed time horizon identified on a contract. We assume that the product failure rate is λ and the expected number of failures during the contract horizon is $E[\lambda]$. The repair time of a failed unit is fixed to l, and it is quantified by Mean Time to Repair (MTTR). Mean Time between Failures (MTBF) and MTTR is utilized to quantify product and service quality. The supplier can decrease MTBF by investing in improving product quality. We calculate the MTBF with the following equation:

$$MTBF = 1/\lambda \tag{26}$$

One of the decision variables quality improvement efforts of the supplier is represented with ϙ. Quality improvement effort ϙ is a function of MTTR and MTBF. Thus, the following equation quantifies the quality improvement efforts of the supplier, which we will call quality efforts on the rest of the paper:

$$ϙ = 1/(MTBF * MTTR) = 1/(\lambda * l) \tag{237}$$

The quality effort has a theoretical minimum and maximum. The theoretical minimum level is the case where the supplier does not take any action to improve product quality. Thus, minimum ϙ refers to existing product quality. As the investment in product quality improvement effort increases, the rate of change on actual product quality will diminish. The supplier will have a certain maximum product quality that can be achieved. Therefore, $\overline{ϙ} > ϙ > \underline{ϙ}$, the range of quality efforts will be between the theoretical maximum and theoretical minimum.

We assume that quality effort is not verifiable by the customer. Since the supplier both sells the product and provides after-sales services, the information asymmetry on product quality can lead to a moral hazard problem. The customer manages this problem by offering a contract to the supplier in the form of either a warranty contract or a performance-based contract. The contract is designed to influence the suppliers' behavior. Our model focuses on determining optimal supplier decisions under different contracts. We do not attempt to find the optimal contract parameters. We refer our readers to Kim et al. (2017) and Kim at al. (2007) for models that find optimal contract parameters on after-sales service contracts. When a product fails, the supplier can change the failed unit with the working one from the spare parts inventory, if available. The decision variable s represents the number of spare units in the inventory. In the initial phase of the contract, the supplier manufactures $N + s$ number of identical products. The customer purchases N of the manufactured product, and the supplier stores s of the products in the spare part inventory. The supplier will be responsible for maintaining, storing, repairing of $N + s$ products in the system. Hence, our model examines a case where the inventory is managed by the supplier, a Vendor Managed Inventory system.

Product Availability and Repair Process

The repair process is modeled according to the spare-part provisioning literature. The standard assumptions for the repair process are adopted by Kim et al. (2017). The repair process is represented by an M/G/1 queue: The product failures follow a Poisson distribution, the service time is fixed with a general distribution, and there is only one service center. When the product fails, the supplier is obliged to replace the failed part with a working unit if there is one in the spare parts inventory. If there is a stock out for spare parts, a backorder occurs. We assume that the repair process employs a one-for-one inventory policy on replacing a failed unit.

The number of units that are in the repair process on a random time, inventory on-order, is represented by $O[\varrho]$. Inventory on-order has a mean of $1/\varrho$. The supplier can reduce the number of inventories on-order by investing in product and process quality. Inventory on-order has a direct effect on two important parameters -inventory on-hand H and number of backorders B at a random time- which are used to formalize contractual constraints. B and H is a function of spare parts s and inventory on-order levels. The difference between inventory on-order level and the number of spare parts manufactured in the initial phase of the contract will define the inventory on-hand and backorder numbers. If the inventory on-order level is greater than the number of spare parts, a backorder is logged. Therefore, we can calculate the expected number of backorders with the following equation:

$$E[B|\text{ϙ}, s] = max\{O[\text{ϙ}] - s, 0\} \tag{28}$$

The performance of the supplier is measured by the realized product availability. The level of availability of the product is determined by the number of backorders. Availability decreases when a backorder is logged. We quantify the availability below based on the number of backorders and the total number of products:

$$E[A|\text{ϙ}, s = 1 - E\left[B \mid \text{ϙ}, s\right]/N \tag{29}$$

The most common discreet probability distribution to model failure rates is Poisson distribution in maintenance and repair literature. Given a large number of observations, Poisson distribution can be approximated to a binomial distribution (Sherbrooke, 1986). With N identical products, failure process in our model will be modeled with standard normal distribution for tractability of the calculations. Based on normal binomial distribution assumptions, we assume that the inventory on-order $O[\text{ϙ}]$ has the mean of $1/\text{ϙ}$ and the variance of $1/\text{ϙ}$. The probability density function of the failure distribution is given as:

$$f(x) = \frac{1}{\sqrt{2\pi}} e^{\frac{-x^2}{2}} \tag{30}$$

Accordingly, the cumulative distribution function of the failure distribution is formulated as:

$$F(X) = \int_{-\infty}^{X} \frac{1}{\sqrt{2\pi}} \times e^{\frac{-x^2}{2}} \times dx \tag{31}$$

Based on the equations (5) and (6), the loss function of the normal distribution as can be provided on the following equation:

$$L(x) = f(x) \times x\big(1 - F(X)\big) \qquad (32)$$

We can calculate the z score of the distribution with the given quality efforts and the spare parts inventory level:

$$z \equiv \frac{s - E[O(ϙ)]}{\sqrt{Var[O(ϙ)]}} = \frac{s - \left(\frac{1}{ϙ}\right)}{\sqrt{1/ϙ}} \qquad (33)$$

Finally, the expected number of backorders can be calculated with the help of loss function. We quantified the expected number of backorders with the following function:

$$E[B|s, ϙ] = L\,(z)/\sqrt{ϙ} \qquad (34)$$

Cost Variables

We consider the cost from both the customer's perspective and the supplier's perspective on the modeling process. From a customer perspective, two cost components are identified that have a significant effect on the total cost: (1) D_i, cost of inconvenience as a result of unexpected product failures and unscheduled maintenance, and (2) D_b, backorder costs due to business loss. From a supplier perspective, there are three types of cost components related to the after-sales services:: (1) $C_q(ϙ)$, cost of quality improvement efforts, (2) C_m, cost of unscheduled maintenance when the product fails, and (3) C_s, the cost of producing and storing spare parts.

The amount of investment on increasing the product and service quality by the supplier is represented by $C_q(ϙ)$. We calculate $C_q(ϙ)$ in terms of the monetary amount. We assume that $C_q(ϙ)$ will be an exponential function where the cost of the supplier's quality effort will increase exponentially. In practice, the supplier can improve the product quality up to some point, but after a certain point, more investment in quality efforts will bring very little to no improvement. Therefore, we assume that the limit of $C_q(ϙ)$ the function will approximate to infinity at a certain level. The cost of quality improvement efforts is represented with the following function.

$$C_q(ϙ) = (ϙk)^n - t, n > 3 \tag{35}$$

The constants $k, t,$ and n are used to make the limit of the cost function infinite. When $n > 3$ the derivatives of the cost function, $C_q{}'$,$C_q{}''$,$C_q{}'''$, are greater than 0.

The second component of the supplier's after-sales service cost is unscheduled maintenance and repairs. The supplier is responsible to perform an unscheduled repair and maintenance when the products fail unexpectedly. If the cost of each unscheduled maintenance and repair is represented by m, the total cost of the unscheduled maintenance and repairs will be the product of failure rate and unit cost of unscheduled operations. Thus, we can calculate the total cost of unscheduled maintenance and repairs with the following equation:

$$C_m = \lambda \times m \tag{36}$$

Finally, the supplier will hold an inventory of spare parts to meet the availability requirement. Each spare unit will have a manufacturing cost and holding cost. If the sum of the holding cost and the manufacturing cost is equal to h, we can represent the total cost for the spare units, C_s, with the following function:

$$C_s = s \times h \tag{37}$$

From the customer's perspective, there are inconveniences and backorder costs. We will use these cost components on the calculation of the first-best solution. The inconvenience cost is the result of unexpected product failures. If the inconvenience cost for each product failure is represented by i, we can determine the total cost of inconveniences with the following equation:

$$D_i = \lambda \times i \tag{38}$$

The backorder cost is a result of a business loss for each logged backorder. The opportunity cost for loss of business is represented by b. Recall that the expected number of backorders at a random time is given by $E[B|s,\varrho]$. Then, we can quantify the total cost of backorder for the customer as follows:

$$D_b = E[B|s,\varrho] \times b \tag{39}$$

Contracts

Two contractual scenarios are compared where the customer offers a contract to the supplier for after-sales services. The contract specifies the payment structure and the responsibilities of the supplier. The payment amount to the supplier is represented by T. For the first case, the customer demands after-sales services and governs the relationship with a warranty contract. Based on the contractual agreement, the supplier is responsible for covering α percent of unscheduled maintenance costs as a part of the warranty. Bakshi et al. (2015) provide an after-sales service contract where supplier covers the α percent of the after-sales cost. We adopted a similar contract model for warranty contracting. Once contract terms are finalized, the supplier selects the optimal quality improvement effort ϱ^* and spare parts amount s^*. The customer first makes a payment amount of ω. When a product failure occurs, $(1-\alpha)$ percent of the unscheduled maintenance cost is compensated by the customer. The total payment T_w to the supplier with a warranty contract, therefore, is the sum of initial payment and compensation for unscheduled maintenance costs.

$$E[T_w|\varrho^*, s^*] = \omega + (1-\alpha) \times C_m \tag{40}$$

For the second case, the customer offers a performance-based contracting for necessary after-sales services. In this scenario, the supplier is offered a larger amount of initial payment ρ to make the performance-based contract more desirable to other types of contracts. Once the contract terms are finalized, the supplier decides on the quality efforts and spare parts provisioning. The supplier chooses the optimal ϱ^{*} and s^{*} to maximize the profit. The supplier's optimal decisions will have a direct effect on the realized number of backorders during the contract horizon. The supplier compensates the customer for each backorder instances at the rate of ν. Accordingly, the total amount of payment T_p the customer makes to the supplier during the contractual relationship can be calculated as:

$$E\left[T_p \middle| \varrho^{*}, s^{*}\right] = \rho - \nu \times E[B|\varrho^{*}, s^{*}] \quad (41)$$

Our cost functions and payment functions in this study are linear. The payment functions and the cost functions help us in finding the optimal values for the decision variables.

The Supplier Behavior Analysis

Three optimization models are generated to compare different after-sales service scenarios. First, we modeled the first-best solution as the basis of the comparison. Secondly, we find optimized the supplier decisions under the warranty contract. Thirdly, we find the supplier's maximum profit under performance-based contracting. We compare the results of the warranty contracting and the performance-based contracting with the first-best solution to analyze which contract performs better on product quality improvement efforts.

First-Best Solution

The first-best solution is the benchmark case for our analysis. For the first-best solution case, we assume that the customer and the supplier are both a subsidiary of a parent company. The decisions in terms of spare part provisioning and quality efforts are made by the parent company. The objective of the parent company is minimizing the total cost of after-sales services while meeting the target availability level. We define the problem of the parent company with the following objective function:

$$MinE[C|\varrho^{FB}, s^{FB}] = C_q + C_m + C_s + D_i + D_b \quad (42)$$

Subject to

$$E[A|\varrho^{FB}, s^{FB}] = A_{min} \quad (43)$$

$$\overline{\varrho} > \varrho^{FB} > \underline{\varrho} \quad (44)$$

where $E[A|\varrho^{FB}, s^{FB}]$ and $E[C|\varrho^{FB}, s^{FB}]$ are expected availability level and expected total cost when optimal decision variables are selected. The model with objective function and the constrains results in the optima quality improvement effort and spare part inventory level when the decision is made by the parent company.

Profit Maximization Under the Warranty Contract

Under the warranty contract, the supplier is responsible for bearing a certain share of the unscheduled maintenance cost. The share of the cost covered by the supplier is defined with variable α. The regular product warranty covers all the costs of product failures by either repairing or replacing the product. Warranty for capital goods, however, the supplier can compensate only a certain part of the cost of product failure. There will be a cost component that will not be covered by the warranty. Thus, we assume that the customer pays $1 - \alpha$ portion of the unscheduled maintenance cost. We assume that the customer and the supplier negotiate the warranty coverage rate α before the contract is finalized. The expected amount of payment to the supplier is provided on the equation (40). Once the warranty rate is finalized with the contract, the supplier selects the optimal parameters for decision variables ϱ^* and s^* to maximize the profit. We formulate the objective function of the supplier under the warranty contract with the following equation.

$$Max\ \pi|\varrho^*, s^* = E[T_w|\varrho^*, s^*] - SC \quad (45)$$

Subject to

$$E[A|\varrho^*, s^*] = A_{min} \quad (46)$$

$$\overline{\varrho} > \varrho^* > \underline{\varrho} \quad (47)$$

where SC is the total expenditures that the supplier spends during the contract horizon. The supplier's spending includes the cost of improving quality, cost of inventory for spare parts, and cost of unscheduled maintenance. The supplier selects the optimal decision variables that maximize the objective function. Constrains (46) and (47) are target availability level and theoretical bounds of the quality improvement efforts, respectively.

Profit Maximization Under a Performance-Based Contract

Under the performance-based contract, the supplier is paid based on realized product availability rather than goods and service provided during the contract horizon. We demonstrate on equation (4) that the realized availability level is a function of the expected number of backorders. The customer makes an initial payment that is larger compared to a warranty contract. On the other hand, the customer is penalized for every realized backorder. The supplier maximizes the profit by ensuring product availability. We assume that the customer compensated up to a certain amount of target availability. The expected amount of payment to the supplier under performance-based contracting is $E\left[T_p \middle| \varrho^*, s^*\right] = \rho - \nu \times E[B|\varrho^*, s^*]$. The penalty rate ν is ex-ante part of the contract. The supplier and the customer can negotiate on the penalty rate before the contract terms are finalized. The supplier selects the optimal decision variables ϱ^* and s^* once the contract is signed. With the optimal quality improvement efforts and the spare parts inventory level, the supplier attempts to maximize the profit of after-sales services. Following objective function calculates the expected profit for the supplier under performance-based contracting:

$$Max\ \pi|\varrho^*, s^* = E\left[T_p \middle| \varrho^*, s^*\right] - SC \quad (48)$$

Subject to

$$E[A|\varrho^*, s^*] = A_{min} \quad (49)$$

$$\overline{\varrho} > \varrho^* > \underline{\varrho} \quad (50)$$

where SC represents the total cost for the supplier regarding after-sales services during the contractual relationship. Supplier cost SC is a combination of inventory cost, quality improvement costs, and cost of unscheduled maintenance. The objective function of the supplier is constrained by minimum target availability and theoretical bounds of the quality improvement efforts. Constraint (49) represents minimum target availability. Constraint (50) provides theoretical limits of the quality improvement efforts.

Solution Algorithm

Due to the formulation of the quality improvement effort cost, our objective functions have non-linear components. The appropriate solution approach for non-linear objective functions would be a goal programming model. With non-linear objective functions combined with integer programming, our solution is difficult to solve with linear programming approaches (O. K. Gupta & Ravindran, 1985; Jin & Wang, 2012). We used the heuristic approaches with a genetic algorithm to find the optimal solutions for each scenario. Existing algorithms on non-linear programming solve the objective function step by step solutions. Random variables are first selected to find the value of the objective function. Then, the new parameters are used the calculate the objective function. On each step, the improvement on the objective function is recorder if there is one. Successive solutions are found, and the solutions are branched out the find the integer values for decision values. Recently, heuristic approaches and genetic algorithms are used to find the optimal solution to non-linear goal programming in performance-based logistics literature (Jin & Wang, 2012; Nowicki et al., 2008; Uvet et al., 2019).

Since our model has only two decision variables ϱ and s, we solve the objective functions with the iteration method to find optimal decision variables. We applied the following steps for the solution procedure. First, we assume that there are no spare parts is manufactured initially. While we set the $s = 0$, we assume that initial quality improvement effort is equal to theoretical minimum, or existing quality level, $\varrho = \underline{\varrho}$. Then we gradually increased the quality effort from $\underline{\varrho}$ to theoretical maximum $\overline{\varrho}$ in very small quantities and observed the objective function. After we find the maximum profit for the zero-inventory case, we increased inventory level to 1 and observed objective function with each different value of quality efforts. We iterated the same procedure by increasing the spare-part inventory by one unit on each iteration. If the profit is greater than the previous iteration, we continued to the next iteration. If there is no improvement in the objective function, we stopped the iteration and selected the observed ϙ and s on the last iteration.

Numerical Example

The data for numerical experimentation is collected from existing literature on after-sales service contracts. Using the literature for collecting numerical data is an existing procedure in the after-sales services literature. For example, Jin and Wang (2012) use the data provided on Kim et al. (2007) on numerical experimentation. Bakshi et al. (2015) collect the data for the numerical example from various existing academic articles. Similarly, our cost data on the numerical example are drawn from Bakshi et al. (2015). Our numerical study optimal resource allocation values for quality improvement efforts and spare part provisioning while maximizing the supplier's profit under the contractual agreement.

For numerical experimentation, we investigate an aerospace company. The company manufactures complex avionic systems and provides after-sales support services for the customers. We assume that backorder cost is b = \$2,000,000 for each backorder logged during the contractual relationship. The theoretical minimum level for the quality improvement effort is set to $\underline{ϙ} = 1/N$. The company sells $N = 150$ avionic systems to the customer. The maximum quality improvement effort that the supplier can achieve is $\overline{ϙ} = 0.1$. The sum of manufacturing and inventory holding cost for each spare unit is h = *\$70,000.* Each failure causes an inventory cost of i = *\$175,000* to the customer. The cost of an unscheduled maintenance cost for each product failure is m = \$800,000. We utilized the cost data provided on Bakshi et al. (2015) to calculate the total cost of providing after-sales services. Since the goal of this research is to find optimal supplier behavior rather than optimal contract parameters, we make some assumptions on the contract parameters. Under the warranty contract, we assume that the initial payment to the supplier is ω = *$10,000,000.* The supplier is compensated α = *0.5* part of the total unscheduled maintenance cost. Under the performance-based contracting, the customer makes an initial payment amount of ρ = *$12,000,000* to the supplier. Then the penalty rate for each logged backorder is set to v = *$100,000.* We run our model to analyze each contracting scenario to find optimal decision variables ϙ and s such that maximizes the expected profit from after-sales services. Table 3.2 provides all the numerical data used on numerical experimentation.

Table 3.2: Numerical Experimentation Parameter Values

Parameter	Value	Parameter	Value
b	$2,000,000	ω	$10,000,000
N	150	k	1,000
h	$70,000	t	10,000
i	$175,000	n	4
m	$800,000	α	0.5
l	3	A_{min}	0.95
ρ	$12,000,000	ν	$100,000

Optimal values of ϙ and s under the first-best scenario, under the warranty contract, and under the performance-based contract are shown in Table 3.3. The optimal decision variables show that as the supplier invests more in product quality improvement effort, the need for spare-part provisioning decreases. While the warranty contract requires higher values for spare parts inventory levels, the performance-based contracting requires increased spending on product quality improvements, which provides the second-best solution. The numerical experiment presents that the supplier has less interest in improving the product quality under the warranty contract compared to the performance-based contract. The supplier is, however, better off with increasing the product quality when the payment for the after-sales services is made based on the realized performance. Figure 3.1 visualizes the relationship between inventory levels and product quality under different scenarios.

The results in Table 3.3 shows that performance-based contracting comes closest to the first-best solution. Thus, the performance-based contracting scenario provides a second-best solution. The profit π values show that the supplier may act opportunistically to increase the profit by selling lower quality products.

Table 3.3: Optimal Decision Variables, Total Cost, and Profit, $A_{min} = 0.95$

Parameter	First best	Warranty	Performance-based
ϱ	$2,416,198	$1,550,765	$2,072,897
s	18	21	19
SC	$10,432,938	$10,565,333	$10,422,326
π	-	$3,206,951	$827,678
TC	$26,911,170	$27,215,678	$26,957,747

Figure 3.1: Spare parts inventory level and quality improvement efforts under different scenarios

We extended our numerical experiment by running a sensitivity analysis on the target availability constrain. First, we set the target availability constrain $A_{min} = .90$ and run both models for each contractual scenario. We repeated the same process when the value of the target availability is .95 and .99. We should note that as the target availability rate increases, the total cost of the contract (TC) that minimized on the first-best solution decreases. While the warranty contract provides maximum quality level when $A_{min} = .90$, the performance-based contracting achieves maximum quality level when $A_{min} = .99$ out of three parameters. The performance-based contract outnumbers the warranty contract on each target availability level. Moreover, contrary to the warranty contract, the expected profit for the supplier increases as the target availability level set to a higher level. Table 3.4 provides optimal decision variables, the supplier's profits, and the total cost of the contract for the target availability level experimentation.

Table 3.4: Optimal Decision Variables, Profit, Total Cost with Varied Target Availability Levels

Para-meters	$A_{min} = .90$		$A_{min} = .95$		$A_{min} = .99$	
	PBC	**Warranty**	**PBC**	**Warranty**	**PBC**	**Warranty**
ϱ	$2,179,105	$1,404,685	$2,072,897	$1,550,765	$2,233,432	$1,487,582
s	11	14	19	21	27	30
π	$618,200	$3,749,209	$827,678	$3,206,951	$836,233	$2,600,961
TC	$41,398,327	$41,808,535	$26,957,747	$27,215,678	$15,520,964	$15,878,236

Figure 3.2: Quality improvement and supplier profit under different availability levels

We further analyzed the target availability level on performance-based contracting to find optimal availability level that maximizes the supplier profit and quality improvement. Figure 3.2 illustrates that the supplier can achieve maximum profit when the target availability level is .98. Our extended analysis shows that the supplier profit can decrease when $A_{min} = .99$ or higher. Our finding is consistent with the existing literature on performance-based logistics (Jin & Wang, 2012).

We need to note that changing the penalty rate has little or no effect on the optimal decision parameters. The presence of the penalty rate is enough for the supplier to change the behavior on product quality and spare part provisioning.

Conclusion

With the help of genetic algorithm and heuristic approaches to optimization modeling, we numerically experimented the optimal supplier behavior on after-sales service contracting for complex capital goods. We mainly focused on a performance-based contract where payment terms tied to the realized performance of the supplier and compared it to a warranty contract where the supplier is responsible for a certain portion of the product failures. A performance-based contract is designed to protect the customer from the supplier's opportunistic behavior by incentivizing the supplier on investing product quality improvement efforts. Although there are numerous researches on performance-based contracting, our paper provides simple numerical experimentation with real-life cost data and brings warranty concept into the picture for numerical comparison.

Our numerical study shows that the warranty contract is not as efficient as a performance-based contract in motivating the supplier to invest more in product quality. Under the warranty contract, the supplier prefers to meet target availability criteria by increasing the spare part inventory levels. Under the performance-based contracting, however, the supplier can maximize the after-sales service profit by only increasing the product quality compared to the warranty contract. Compared to the first-best solution, where the decisions are made by a single parent company of both parties, a performance-based solution comes closest to achieving the desired product quality. The result closes that gap between the first-best solution and the second-best solution that arise in the previous study that compares the warranty contract to the time and material contracts.

Furthermore, we find that as the target availability level increases, the supplier can achieve a higher level of profit. The successful application of the performance-based contract for the maximum quality and supplier profit depends on selecting the achievable target availability level. Our numerical experiment shows that the supplier can achieve the maximum profit at a certain target availability level. After the maximum achievable profit, the expected supplier profit decreases as the customer demands more on target availability level. However, the performance-based contract achieves maximum profit from the supplier at the higher target availability level compared to the warranty contract. The same case applies to product quality as well. The performance-based contract accomplishes maximum product quality at a higher target availability level than the warranty maximum. The practitioners from both parties should negotiate the desired performance level that is tied to product availability before finalizing the long-term after-sales service contract.

Finally, our study comes with some limitations. For example, the payment function on our performance-based contracting scenario is linear. Future studies can investigate more complex payment functions such as the conditional function that can be seen on step revenue function (Nowicki et al., 2008). As our model makes various assumptions on the model building, future research can extend our study by relaxing those assumption to improve model validity. More empirical data on product failure rates with an accurate distribution model can enhance the model quality for a better understanding of after-sales service contracts.

CONCLUSIONS

In the after-sales service research, the lack of numerical experimentation and the use of real-life data utilization for explaining mathematical model causes theoretical and analytical problems. This research undertakes these issues by using real-life cost data from existing literature to enhance our understanding of after-sales service contracts within the context of the capital goods industry. The research involves three essays using multiple quantitative and qualitative methods such as optimization models with profit maximization and systematic literature review in different after-sales service services for complex capital goods.

Essay 1 classifies the existing mathematical models related to after-sales services to increase our knowledge of the assumptions and the approaches to the modeling process. We identified that there is a research gap that systematically investigates the mathematical models of after-sales service contracts. We tackled this gap to promote some future research avenues in after-sales services. The categorization process shows that it is vital to obtain real-life data to numerically study the existing analytical models. Current research is important to extend theory and the extension of the basic theory to real data will accelerate the transition from theory to practice.

Essay 2 utilizes optimization models and genetic algorithms to bring warranty contract into the context of after-sales services for the capital goods. Our study shed lights on the effect of warranty contract on the supplier's quality improvement efforts. The numerical experiment with real-life cost data shows that the warranty contract performs better than no warranty scenario in terms of the supplier's investment in product quality. Without a proper warranty mechanism, the supplier may behave opportunistically to maximize the after-sales service profit by investing in spare-part provisioning at the expense of product quality. Finally, we stress that the successful implementation of a warranty contract is dependent on the right target availability level and warranty coverage rate. A higher-warranty coverage rate may result in increased quality improvement with the risk of the supplier's resentment from the contractual relationship. We posit that the customer's negotiation skills play an important role in determining the warranty coverage rate.

Essay 3 is built upon the findings of essay 2. First, the gap between the first-best solution and the warranty contract prompted our research to find a better alternative to the warranty contract in the after-sales service context. Based on the categorization structure of essay 1, we directed our focus on performance-based contracting. We employed an optimization model to compare performance-based contracting to warranty contracting. Our numerical experimentation reveals that, compared to a warranty contract, performance-based contracting achieves higher standards on incentivizing the supplier to improve product quality. Moreover, the maximum profit from the after-sales service is dependent on selecting the optimal target availability level. Our model can help practitioners to find optimal target availability levels based on industry-specific cost data.

Collectively the three studies presented in this research move the understanding of after-sales service research forward. As a result, the research has implications for practitioners and adds to the literature on after-sales service research.

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