Who Should Bear the Risk? A Theoretical and Behavioral Investigation of After-Sales Service Contracts

Özge Tüncel
School of Industrial Engineering, Eindhoven University of Technology, o.tuncel@tue.nl

Rob Basten
School of Industrial Engineering, Eindhoven University of Technology, r.j.i.basten@tue.nl

Michael Becker-Peth
Rotterdam School of Management, Erasmus University, m.beckerpeth@rsm.nl

Since downtime is expensive, it is key to use the right after-sales service contract to achieve high equipment availability. Resource-based contracts (RBCs) are common, but they fail to motivate suppliers to provide reliable products and services as suppliers are paid for their after-sales services. Performance-based contracts (PBCs) have been proposed as a way to solve this issue, as it shifts much of the downtime risk to the supplier by making him responsible for machine uptime, but then customers might reduce care efforts. We are the first to analytically incorporate the care in equipment availability. We propose the full-care contract (FCC) to achieve both high reliability and care, and maximize the chain efficiency. We find that only the FCC can achieve full chain efficiency. After discussing potential behavioral factors in this context, with a focus on risk aversion, we conduct a lab study with decision makers as suppliers. Experimental results confirm that the FCC achieves higher total profits than the PBC and RBC. We further find that subjects are more likely to switch from the RBC to the FCC than to the PBC, despite the higher risk involved in the FCC. Finally, we observe that effort levels set by suppliers are above normative predictions and we discuss potential explanations for this result.

Keywords: behavioral operations management; service contracts; resource-based; performance-based; risk premium

---

1. Introduction

For many products with a long life cycle, such as production equipment or trains, providing customer support can be more profitable than selling the product initially, because such support provides long-lasting revenue to the supplier. Cohen et al. (2006) state that companies focusing on the design and production stages, but ignoring customer support in delivering value to customers, have a difficult time competing with companies that do pay attention to support. According to Bain & Company (2015), after-sales services can significantly increase revenue (by 22%), with an even greater increase in profit (39%) for a broad cross-section of industrial companies. Moreover, the service business of these industrial companies grew annually by 9% between 2010 and 2013, while the new product sales business grew only 5%.

In addition to providing an increase in revenue, after-sales services are recurring, and thus revenues are more stable. Furthermore, after-sales services are becoming more important for suppliers as customers' expectations are rising. Bain & Company (2015) shows that customer satisfaction increases with a dedicated service supply chain. Furthermore, Cohen et al. (2006) state that customers' intention to repurchase equipment is highly correlated with the quality of the after-sales services. Therefore, to stay competitive and increase the financial performance of the company, suppliers are required to pay greater attention to their after-sales services. These developments require suppliers to find a business model that can satisfy customers' increasing expectations of after-sales services while keeping costs at a minimum.

The resource-based contract (RBC) has commonly served as the after-sales service agreement. Under this contract, the customer pays the supplier for resources used when the customer needs service. However, the RBC allocates the risk of machine breakdowns to the customer and increases the moral hazard risk of the supplier, because the repair activities are profitable. An alternative to the RBC is the performance-based contract (PBC), in which the supplier compensates the customer for breakdowns while the customer makes a higher fixed payment to the supplier. Unlike the RBC, the PBC is designed to encourage the supplier to maximize the quality of after-sales services by putting the risk on the supplier. For this reason, customers are increasingly preferring to use the PBC to motivate suppliers to increase their after-sales service efforts. Recent literature also favors the use of the PBC because the PBC can align the incentives of customers, to maximize machine uptime, with the incentives of suppliers, to minimize downtime, and thus, customer compensations (Mirzahosseinian and Piplani 2011; Kim et al. 2017).

However, many suppliers still hesitate to choose the PBC over the RBC in practice. Case studies on PBCs suggest that an important factor resulting in the lack of supplier motivation to increase the reliability effort is a subpar incentive offered to suppliers to bear the breakdown risk (Harada 2010). The up-front payment in the PBC should be higher than the up-front payment in the RBC so that suppliers are willing to increase their effort. Therefore, finding a risk premium that can not only result in an increased effort behavior by the supplier but also keep the customer's costs at an acceptable level is an important element in the successful adaptation of PBCs in practice.

Hou and Neely (2018) present another reason behind suppliers' reservations, namely the additional risk that comes with the lack of control over customer behavior. For example, a pilot removing a communication plug carelessly could cost the supplier more than 20,000 euros (Ng et al. 2009). Our conversation with after-sales executives at a multi-national food processing equipment and services company confirms the supplier's concern to offer the PBC to its customers. Empirical studies report mixed results on the performance of the PBC in practice (Kirk and DePalma 2005; GAO 2008;

Harada 2010). To explain this mismatch between practice and theory, Guajardo et al. (2012) conduct an empirical study on service contracts of Rolls-Royce for its aircraft engines. They compare the engine performance of customers under the RBC with that of customers under the PBC. While they do not find a significant difference initially, a deeper analysis shows that the supplier actually increases the reliability effort under the PBC, while the customer becomes more careless. Analytical studies of service contracts ignore the impact of the care level of the customer on machine availability and thus fail to capture this drawback of the PBC. Therefore, mixed findings on the PBC's success in practice could be explained by the trade-off that occurs between supplier's motivation to invest in reliability and the customer's motivation to invest in care.

Achieving both high care and reliability levels requires another type of contract. Vanderlande, the global market leader of value-added logistic process automation at airports, provides some customers the PBC plus operation service. In this case, Vanderlande not only provides equipment and maintenance but also operates the equipment at customers' airports (Vanderlande 2020). The construction industry has introduced the design-build-operate-maintain contract, with a similar idea of achieving better performance by shifting all responsibilities to one company (Dahl et al. 2005). Such a contract allows the supplier to control both reliability and care levels. Therefore, the supplier will be motivated to optimize both the reliability and care resulting in minimum failure rate and the first-best solution. Moreover, the supplier will gain a better understanding of the problems with the equipment, and it can provide a feedback loop to improve future designs based on the experience with the current equipment. We refer to this contract as the full-care contract (FCC). To our knowledge, although this contract is used to some extent in practice, it has not yet been studied analytically.

The findings in the literature and examples in practice motivate three specific research questions that we address herein: (1) Can the PBC result in higher machine availability and chain profit than the RBC if machine failures depend on both care and reliability? (2) Can the FCC solve the moral hazard problem regarding both reliability and care investments and thereby result in higher machine availability than both the RBC and PBC? (3) Can suppliers be induced to bear the failure risk with the PBC and FCC in practice?

We answer these questions in three steps. First, we analytically examine the three contracts and compare them. Second, we discuss the potential behavioral factors that can affect the performance of these contracts, with a focus on risk aversion. Third, we conduct laboratory experiments with suppliers as decision makers to evaluate how these contracts perform. Our analytical findings show that suppliers can be motivated to provide higher reliability with the PBC than the RBC. However, customers have less motivation to take good care of machines when offered the PBC than the RBC. Therefore, the PBC will outperform the RBC when reliability is more important or cheaper to invest in than care. However, neither the PBC nor the RBC can optimize the machine availability or the chain profit. The FCC will allocate both these decisions to the supplier along with the risk. Thus, it will encourage the supplier to maintain the equipment at both high reliability and care levels, optimizing the machine availability and maximizing chain efficiency. Our behavioral study also indicates that the supplier might request a higher risk premium under the FCC than the PBC because the supplier's profit variance is more likely to be higher than under the PBC. The option to share the risk under the PBC can result in a lower total profit variance. Because the FCC can maximize the chain profit, its use might motivate the supplier to take over the risk despite a potentially high risk premium. However, the PBC also has the potential to convince the customer and supplier to share the risk, even though the chain profit cannot be maximized given its potential for a lower total risk premium.

In our lab experiments, we find that subjects choose effort levels above the normative predictions (for the reliability in the PBC and the reliability and care in the FCC). Although these deviations affect profits, the FCC remains most profitable, while the PBC remains more profitable than the RBC, for both the supplier and the total chain. We next find that suppliers are more likely to switch from the RBC to the FCC than from the RBC to the PBC. This is partly due to the higher chain profits that can be distributed between the customer and supplier and partly to the involved risk premiums. We find that suppliers demand a significant risk premium for switching from the RBC to either one of the riskier contracts, as suggested by our behavioral study. However, the premium does not solely depend on the risk amount in the supplier's payment, as we find that the risk premium under the FCC is not significantly higher than it is under the PBC (while the profit variance is). To explain the too high effort levels and the stable risk premiums, we explore sustainability concerns as a potential explanation.

This paper makes several contributions: (1) We update contracting theory by incorporating the care level in the failure probability and find that neither the PBC nor the RBC results in first-best chain efficiency and machine availability. (2) We introduce a new contract, the FCC, which can solve the moral hazard problem of both the customer and the supplier and attain first-best efficiency and availability. (3) We are the first to conduct lab experiments with service contracts, in which we collect data on suppliers' effort decisions under a risky contract and their risk premium requirements to give up a risk-free contract. (4) We find that risk, bounded rationality, and mean anchoring are not the primary behavioral factors influencing decision makers; sustainability concerns also be driving the results. (5) We analyze the risk premiums demanded by suppliers to switch to risky contracts and analyze the likelihood of agreement.

The rest of this paper proceeds as follows. After a brief literature review in Section 2, we lay out the problem context in Section 3 and the analysis in Section 4. Then, we introduce potential behavioral factors that can make decision makers deviate from normative predictions in Section 5. Afterwards, we conduct laboratory experiments to analyze decision making with service contracts in Section 6. We conclude in Section 7.

2. Literature Review

Cohen et al. (2006) emphasize the importance of business models between after-sales service supply chain members to manage successful chains. They argue that the incentives of all companies in the after-sales supply chain are determined by these models. Moreover, they suggest that companies are better off with performance-based business models when the supplier can bear the risk of equipment ownership. Since Cohen et al. (2006), PBCs have attracted significant attention in the literature.

Kim et al. (2007) are one of the first to analytically examine service contracts with a focus on PBCs. They compare the PBC with the traditionally used fixed-price and cost-plus contracts and suggest that the first-best solution can be achieved through the PBC if companies are risk neutral. However, they assume that the probability of machine failure is an exogenous variable that depends on neither the supplier's nor the customer's effort choices. Kim et al. (2017) analytically compare the RBC and PBC, modeling machine availability as a function of reliability and incorporating the cost of increasing the reliability of the supplier's profit function. They find that the PBC can motivate the supplier to increase the reliability effort because his service revenue can actually grow with higher reliability, which is the opposite with the RBC. Moreover, they conclude that the highest efficiency can be achieved with the PBC when the supplier takes full ownership of the machines.

Roels et al. (2010) analytically examine the PBC not in the manufacturing industry but in collaborative services such as consulting, in which they incorporate the effort levels of the companies as a factor in productivity. They find that the RBC is better when the productivity depends more on the buyer's effort level than the vendor's effort level, while the PBC works better when the output depends equally on the efforts of both companies. Similarly, we also incorporate both the supplier and customer effort as factors affecting machine availability and find that the RBC (time-and-materials contracts) is better at motivating the customer to exert effort than the PBC. However, Roels et al.'s (2010) findings are based on the assumption that the buyer exerts high efforts only when the vendor exerts high efforts, and vice versa, resulting in different conclusions. In our study, we focus on the after-sales supply chain with original equipment manufacturers and follow Kim et al. (2017) but add the customer's effort as a factor in the machine availability.

While the theoretical literature finds strong support for the PBC's ability to increase machine availability and chain efficiency, the empirical literature does not always support this finding. Kirk and DePalma (2005) find a significant cost of using PBCs to the customer, which in their case is the U.S. Navy. They analyze 13 contracts but find mixed results regarding the contract's success.

Moreover, a report from the U.S. Government Accountability Office (GAO 2008) indicates that whether the PBC can provide a cost reduction for the Department of Defense is unclear, making it less desirable. Harada (2010) conducts a detailed analysis on PBCs and presents cases in which these contracts do not increase reliability. He further highlights the risk premium discussion as an essential part of PBCs, which needs further attention.

To explain the mixed findings on the success of PBCs in practice, Guajardo et al. (2012) carry out an empirical analysis of Rolls-Royce's service performances for its aircraft engines. They compare Rolls-Royce's service performance at customers choosing a PBC with service performance at customers choosing an RBC (time-and-materials contracts). They find that the availability of engines is not significantly different between the two customer groups. However, they suggest that customers who are more likely to take poor care of machines choose the PBC more often. This may explain the insignificant performance difference between the PBC and the RBC, even if the supplier is more reliable under the PBC. Guajardo et al. (2012) explain that the supplier's reliability is indeed 25%-40% higher with the PBC than the RBC. They conclude that customers' careless actions when the risk is transferred to the supplier with the PBC result in lower engine availability, which is a deviation from the normative prediction on the superiority of PBCs (Kim et al. 2017). In this paper, we aim to close this gap between practice and theory by including machine care as a factor affecting machine availability. Moreover, we explore how the risk premium affects the performances of different service contracts.

The behavioral operations management literature has provided a great deal of insight into supply chain contract mechanisms (for detailed reviews, see Becker-Peth and Thonemann 2018, Chen and Wu 2018, and Donohue et al. 2020). Closely related to our work, Davis et al. (2014) examine the impact of the distribution of the inventory risk on the retailer and the supplier, drawing on the theory Cachon (2004) introduced. They compare the push contract, in which the full inventory responsibility is on the retailer; the pull contract, in which the supplier has control of the inventory and the retailer is never involved; and the advance purchase discount contract, in which the inventory risk is shared between companies. While normative predictions would suggest that the advance purchase discount contract would perform best, they find that pull contracts lead to the highest chain efficiency. They also find that loss aversion and random errors best explain the deviations from normative predictions, which differs from our findings in the after-sales supply chain setting. Service contracts bring a different set of challenges to decision makers, as the underlying theory is different, the availability in addition to chain profit becomes important, and setting a risk premium becomes an essential part of the contract discussion. Nevertheless, certain biases affect traditional supply chain members, such as risk aversion, bounded rationality, and mean anchoring, which we include in our analysis of service contracts, can also affect after-sales chain members.

3. Mathematical Model

We explain the setting that we consider in Section 3.1. The setting is similar to that in Kim et al. (2017), but we simplify it by focusing on a single decision period (i.e., a year), and we extend it by making the machine failure probabilities dependent not only on the reliability level of the machine itself but also on the level of care given to the machine. We then introduce the three types of contracts that may be used by the two companies involved: the RBC (Section 3.2), the PBC (Section 3.3), and the FCC (Section 3.4). All contracts include a fixed payment. In addition, further payments are made between the two companies depending on the number of broken machines. These payments determine how the profit and the risk of machine breakdowns are divided between the two companies. We refer to the customer as 'she' and to the supplier as 'he'.

3.1. Setting

The supplier, who sells machines, offers after-sales services to customers who use the machines. We focus on a contract for one period for one customer using N ($N > 0$) identical machines. The customer produces goods (or provides services) with these machines that are sold to other businesses. Over the contract period, the customer gains a revenue of R ($R > 0$) from the goods produced (or services provided) by a fully functioning machine. However, each machine can break down during the contract period with a certain failure probability. That probability depends on the design of the machine and the maintenance services and care provided to the machine during the contract period. To be precise, the failure probability $P(\tau, \kappa)$ depends on the reliability level τ ($0 \leq \tau \leq 1$), representing the quality of the components used to build the machine and the quality of the maintenance services, and the care level κ ($0 \leq \kappa \leq 1$), representing how carefully the machine is handled and how much daily care is performed, such as cleaning and lubricating. Increasing the reliability or care level decreases the failure probability; that is, i.e., $\frac{\partial P(\tau,\kappa)}{\partial \tau} < 0$ and $\frac{\partial P(\tau,\kappa)}{\partial \kappa} < 0$. We further assume that the reliability and care levels influence the failure probability independent of each other (i.e., $\frac{\partial^2 P(\tau,\kappa)}{\partial \tau \partial \kappa} = 0$). The investments required to obtain a certain reliability and care level are $T(\tau)$ and $K(\kappa)$, respectively, and the costs increase in the required level; that is, i.e., $T'(\tau) > 0$ and $K'(\kappa) > 0$.

The expected number of machines breaking down can be calculated as $\mathbb{E}[B] = P(\tau, \kappa)N$. If a machine breaks down, the customer cannot generate the normal revenue and has a disutility of d ($d > 0$) from that machine. The supplier repairs any broken machines which costs c ($c > 0$) per machine. Then, the expected total chain profit (the sum of supplier and customer profits) is

$$\mathbb{E}\left[\Pi^{\mathrm{t}}(\tau, \kappa)\right] = RN - (d + c)P(\tau, \kappa)N - T(\tau) - K(\kappa), \tag{1}$$

where the first term represents the generated revenue, the second term the expected costs for broken machines, and the final two terms the investment costs.

The stochasticity in the chain profit results from the stochasticity in the number of machine breakdowns, affecting the second term in Equation (1). Higher investments in reliability and care reduce the expected number of machine breakdowns. Therefore, there is a trade-off between reliability and care investment costs on the one hand and breakdown cost on the other hand.

3.2. Resource-Based Contract

Under the RBC, the supplier decides on the reliability level and the customer decides on the care level. Thus, the failure probability depends on the actions of both the supplier and the customer. Depending only on their own actions, related investment costs are incurred by the supplier and the customer. Moreover, the customer makes a fixed payment of w_{R} to the supplier. The customer operates the machines during which a number of machines breaks down. The customer earns R from each intact machine and $R-d$ from each broken machine. Furthermore, the customer reimburses the supplier for repairing broken machines with an amount of r per machine, with $r \geq c$. Therefore, the expected profits of the supplier and the customer are, respectively,

$$\begin{aligned}\mathbb{E}[\Pi^{\mathrm{s}}_{\mathrm{R}}(\tau,\kappa,w_{\mathrm{R}},r)] &= w_{\mathrm{R}} + (r-c)P(\tau,\kappa)N - T(\tau), \text{ and}\\ \mathbb{E}[\Pi^{\mathrm{c}}_{\mathrm{R}}(\tau,\kappa,w_{\mathrm{R}},r)] &= RN - w_{\mathrm{R}} - (d+r)P(\tau,\kappa)N - K(\kappa).\end{aligned}$$

Under this contract, a machine failure negatively affects the customer and positively affects the supplier, as each broken machine costs the customer $d+r$ while the supplier gains $r-c$. The supplier does not face negative consequences from the machine failures and therefore will not be motivated to invest in the reliability at all. However, the customer will be motivated to invest in the machine care to reduce the cost involved with machine breakdowns.

In our analysis, we focus on the RBC, with the customer reimbursement being equal to the repair cost (i.e., $r=c$). In this case, the customer bears the chain risk. If $r>c$, the customer must bear additional risk originating from overcompensating the supplier for his services. The expected profits are then

$$\mathbb{E}[\Pi^{\mathrm{s}}_{\mathrm{R}}(\tau,\kappa,w_{\mathrm{R}})] = w_{\mathrm{R}} - T(\tau), \text{ and} \tag{2}$$

$$\mathbb{E}[\Pi^{\mathrm{c}}_{\mathrm{R}}(\tau,\kappa,w_{\mathrm{R}})] = RN - w_{\mathrm{R}} - (d+c)P(\tau,\kappa)N - K(\kappa). \tag{3}$$

3.3. Performance-Based Contract

Similar to the RBC, under the PBC, the supplier decides on the reliability level and the customer decides on the care level. Thus, the failure probability depends on actions of both the supplier and the customer. Depending only on their own actions, the related investment costs are incurred by the supplier and the customer. Moreover, the customer makes a fixed payment of w_{P} to the supplier.

The customer operates the machines during which a number of machines breaks down. The supplier repairs broken machines at his own expense.

In contrast with the RBC, under the PBC, the supplier compensates the customer for the losses incurred from machine breakdowns with an amount of v per broken machine, with $0 \leq v \leq d$. Thus, the customer earns R from each intact machine and $R-d+v$ from each broken machine. Therefore, the expected profits of the supplier and the customer are, respectively,

$$\mathbb{E}[\Pi_{\mathrm{P}}^{\mathrm{s}}(\tau,\kappa,w_{\mathrm{P}},v)] = w_{\mathrm{P}} - (c+v)P(\tau,\kappa)N - T(\tau), \text{ and} \tag{4}$$

$$\mathbb{E}[\Pi_{\mathrm{P}}^{\mathrm{c}}(\tau,\kappa,w_{\mathrm{P}},v)] = RN - w_{\mathrm{P}} - (d-v)P(\tau,\kappa)N - K(\kappa). \tag{5}$$

3.4. Full-Care Contract

Under the FCC, the supplier takes care of the machines. Therefore, the supplier decides on both the reliability and care levels, and the failure probability depends on his actions only. The supplier incurs the related investment costs for reliability and care. The customer makes a fixed payment of w_{F} to the supplier. The supplier repairs the broken machines and compensates the customer for the losses incurred from each machine breakdown with an amount f, with $0 \leq f \leq d$. Thus, the customer earns R from each intact machine and $R-d+f$ from each broken machine. Therefore, the expected profits of the supplier and the customer are, respectively,

$$\mathbb{E}[\Pi_{\mathrm{F}}^{\mathrm{s}}(\tau,\kappa,w_{\mathrm{F}},f)] = w_{\mathrm{F}} - (c+f)P(\tau,\kappa)N - T(\tau) - K(\kappa), \text{ and}$$

$$\mathbb{E}[\Pi_{\mathrm{F}}^{\mathrm{c}}(\tau,\kappa,w_{\mathrm{F}},f)] = RN - w_{\mathrm{F}} - (d-f)P(\tau,\kappa)N.$$

All decisions affecting the failure probability are solely the responsibility of the supplier, which means that, typically, f should be close to d. In our analysis, we focus on the FCC with the customer compensation being equal to her losses incurred from machine breakdown (i.e. $f=d$). In this case, the customer bears no risk, while the supplier bears the chain risk. The expected profits are now, respectively,

$$\mathbb{E}[\Pi_{\mathrm{F}}^{\mathrm{s}}(\tau,\kappa,w_{\mathrm{F}})] = w_{\mathrm{F}} - (d+c)P(\tau,\kappa)N - T(\tau) - K(\kappa), \text{ and} \tag{6}$$

$$\mathbb{E}[\Pi_{\mathrm{F}}^{\mathrm{c}}(\tau,\kappa,w_{\mathrm{F}})] = RN - w_{\mathrm{F}}. \tag{7}$$

4. Analytical Results

We assume that reliability and care affect the failure probability linearly. We introduce θ, with $0 < \theta < 1$, which represents the impact of the reliability level τ on the failure probability, while $(1-\theta)$ represents the impact of the care level κ on the failure probability. In practice, θ depends on the machine type. For example, the failure probability of a military vehicle that drives through desert sand may depend heavily on the care level, while the failure probability of a solar panel on a roof depends on the care level to only a limited extent. In theory, θ could be either 0 or 1, meaning that either the care level or reliability level do not influence the failure probability. As this case would lead to degenerate results in which zero investment in that level is optimal under any contract, we exclude both options. Moreover, we limit the failure probability between p_l and p_h, with $0 < p_l < p_h < 1$, because even with maximum care and reliability (or no care and reliability), a 0% or 100% failure probability is not possible. We thus calculate $P(\tau, \kappa)$ as

$$P(\tau,\kappa) = p_l + (p_h - p_l)[1 - \theta\tau - (1-\theta)\kappa]. \tag{8}$$

Moreover, we define the machine availability as the opposite of failure probability; that is, i.e. $1 - P(\tau, \kappa)$. The investment cost functions of both the reliability and care levels have a quadratic structure, similar to the investment function requirements in Kim et al. (2017), such that the investment cost is convex and increasing in the corresponding effort level. We calculate $T(\tau)$ and $K(\kappa)$ as

$$T(\tau) = t\tau^2 N, \tag{9}$$

and

$$K(\kappa) = k\kappa^2 N, \tag{10}$$

where t and k are the constants scaling the size of the investment required for reliability and care of the machine, respectively. The values of t and k depend on the machine type and other factors.

Analyzing the given setting, we derive optimal reliability and care levels, the resulting failure probabilities, and the resulting expected chain profit. Lemma 1 shows the first-best reliability level τ^* and the reliability levels that are optimal for the supplier under the RBC, PBC, and FCC: τ^*_{R}, τ^*_{P}, and τ^*_{F}, respectively. Lemma 2 shows the first-best care level κ^* and the care levels that are optimal for the decision maker under the RBC, PBC, and FCC: κ^*_{R} (for the customer), κ^*_{P} (for the customer), and κ^*_{F} (for the supplier), respectively. In this section, we assume that $\tau^* < 1$ and $\kappa^* < 1$. If $\tau^* = 1$ and/or $\kappa^* = 1$, then some of the other levels may also be capped at 1, making some strict inequalities become non-strict. For example, if $\kappa^* = 1$, then the strict inequality in the middle of the expression in Lemma 2 becomes non-strict. Still, all insights would continue to hold. Appendix A provides the proof for these lemmas and all other proofs.

Lemma 1 *For the reliability levels, given $\tau^* < 1$, it holds that*

$$\tau^* = \tau^*_{\mathrm{F}} = \frac{(d+c)\theta(p_h - p_l)}{2t} \geq \frac{(v+c)\theta(p_h - p_l)}{2t} = \tau^*_{\mathrm{P}} > \tau^*_{\mathrm{R}} = 0.$$

Because the supplier is fully reimbursed for his repair activities, machine breakdowns do not affect his profit, and therefore he is not motivated to invest in reliability under the RBC. In line with Kim et al. (2017), we find that the PBC motivates the supplier to attain a higher reliability level. The first-best reliability level is achieved only if the supplier bears all the risk (i.e., if $v = d$). Under the FCC, the first-best reliability level is always achieved.

We further observe that the level at which reliability maximizes the supplier's profit depends, among other things, on the trade-off between the reliability investment cost, t, and the cost of broken machines that the supplier incurs, $d + c$ or $v + c$.

Lemma 2 *For the care levels, given $\kappa^* < 1$, it holds that*

$$\kappa^* = \kappa^*_{\mathrm{F}} = \kappa^*_{\mathrm{R}} = \frac{(d+c)(1-\theta)(p_h - p_l)}{2k} > \frac{(d-v)(1-\theta)(p_h - p_l)}{2k} = \kappa^*_{\mathrm{P}} \geq 0.$$

We observe that the first-best care level is achieved under both the RBC and the FCC. The PBC leads to a strictly lower care level, which is contrary to the advantage of the PBC over the RBC in motivating the supplier to invest in reliability. The reason is that while the customer decides on the care level under the PBC, the resulting disutility from having a low care level is borne partly by the supplier. This decreases the customer's motivation to invest in the care. Even if $v = 0$, such that the supplier does not need to pay the customer for any failure that occurs, the first-best care level is not achieved. The supplier will incur c when a failure happens, so part of the risk is still borne by the supplier. By contrast, if $v = d$, such that the customer is fully compensated and the risk is fully transferred to the supplier, the customer will not invest in care at all under the PBC.

Similar to what we observed for the optimal reliability levels, we find that the optimal level of care depends, among other things, on the trade-off between the care investment cost, k, and the cost of broken machines incurred by the company that decides on the care, $d + c$ or $d - v$.

Using the results in Lemmas 1 and 2, we can compare the failure probabilities that result under these contracts in Corollary 1:

Corollary 1 *Given $\tau^* < 1$ and $\kappa^* < 1$, the failure probability:*

(a) is lower under the FCC than under the RBC; that is $P(\tau^*_{\mathrm{F}}, \kappa^*_{\mathrm{F}}) < P(\tau^*_{\mathrm{R}}, \kappa^*_{\mathrm{R}})$;

(b) is lower under the FCC than under the PBC; that is $P(\tau^*_{\mathrm{F}}, \kappa^*_{\mathrm{F}}) < P(\tau^*_{\mathrm{P}}, \kappa^*_{\mathrm{P}}, v)$;

(c) is equal to first-best under the FCC; that is $P(\tau^*_{\mathrm{F}}, \kappa^*_{\mathrm{F}}) = P(\tau^*, \kappa^*)$; and

(d) is either lower or higher than under the PBC than the RBC; that is, $P(\tau^*_{\mathrm{P}}, \kappa^*_{\mathrm{P}}) < P(\tau^*_{\mathrm{R}}, \kappa^*_{\mathrm{R}}) \iff \frac{(1-\theta)^2}{k} < \frac{\theta^2}{t}$ and $P(\tau^*_{\mathrm{P}}, \kappa^*_{\mathrm{P}}) = P(\tau^*_{\mathrm{R}}, \kappa^*_{\mathrm{R}}) \iff \frac{(1-\theta)^2}{k} = \frac{\theta^2}{t}$.

The FCC implies first-best reliability and care levels and, as such, also implies first-best failure probability. As the reliability level under the RBC is always 0 and thus strictly lower than the first-best, the failure probability under the RBC is higher than that under the FCC. Under the PBC, first-best reliability can be achieved but not first-best care and the reliability level is increasing in v, while the care level is decreasing in v. As a result, under the PBC, the failure probability is higher than that under the FCC.

Corollary 1 (d) shows that the comparison between the RBC and PBC depends on the relative importance of the reliability level compared with the care level, θ, and the costs of investing in both levels, t and k, respectively. If the reliability is relatively important and inexpensive to invest in, the PBC gives the lowest failure probability; by contrast, the RBC gives the lowest failure probability if the care level is relatively important and inexpensive to invest in. This makes sense both when taking the results in Lemmas 1 and 2 into account and intuitively. Under the RBC, the supplier has no incentive to invest in reliability. Therefore, if reliability is important, the RBC is not a good contract. By contrast, because the PBC incentivizes the supplier to invest in reliability, the PBC is a good contract when reliability is important. Using the results in Lemmas 1 and 2 and in Corollary 1, we show the total expected chain profit in Theorem 1:

Theorem 1 *Given* $\tau^* < 1$ *and* $\kappa^* < 1$, *the total expected chain profit:*

(a) is higher under the FCC than under the RBC; that is, $\mathbb{E}[\Pi^{\mathrm{t}}(\tau^*_{\mathrm{F}}, \kappa^*_{\mathrm{F}})] > \mathbb{E}[\Pi^{\mathrm{t}}(\tau^*_{\mathrm{R}}, \kappa^*_{\mathrm{R}})]$;

(b) is higher under the FCC than under the PBC; that is, $\mathbb{E}[\Pi^{\mathrm{t}}(\tau^*_{\mathrm{F}}, \kappa^*_{\mathrm{F}})] > \mathbb{E}[\Pi^{\mathrm{t}}(\tau^*_{\mathrm{P}}, \kappa^*_{\mathrm{P}})]$;

(c) Under the FCC, it is equal to first-best; that is, $\mathbb{E}[\Pi^{\mathrm{t}}(\tau^*_{\mathrm{F}}, \kappa^*_{\mathrm{F}})] = \mathbb{E}[\Pi^{\mathrm{t}}(\tau^*, \kappa^*)]$;

(d) is either lower or higher under the PBC than under the RBC; that is, $\mathbb{E}[\Pi^{\mathrm{t}}(\tau^*_{\mathrm{P}}, \kappa^*_{\mathrm{P}})] > \mathbb{E}[\Pi^{\mathrm{t}}(\tau^*_{\mathrm{R}}, \kappa^*_{\mathrm{R}})] \iff \frac{(1-\theta)^2}{k}(c+v) < \frac{\theta^2}{t}(2d - v + c)$ *and* $\mathbb{E}[\Pi^{\mathrm{t}}(\tau^*_{\mathrm{P}}, \kappa^*_{\mathrm{P}})] = \mathbb{E}[\Pi^{\mathrm{t}}(\tau^*_{\mathrm{R}}, \kappa^*_{\mathrm{R}})] \iff \frac{(1-\theta)^2}{k}(c+v) = \frac{\theta^2}{t}(2d - v + c)$; *and*

(e) is maximized under the PBC when $v^* = \max\left[0, \frac{\theta^2 dk - (1-\theta)^2 ct}{\theta^2 k + (1-\theta)^2 t}\right]$.

A key finding is that the FCC gives the first-best expected chain profit and thus a higher profit than the RBC and PBC. Thus, if the decision makers in both companies are rational, the FCC is the best contract to use. The companies can set the fixed payment w_{F} such that both companies can accrue higher expected profits than under either the other two contracts. This result is because only under this contract are all decisions and all risks at the same company. As such, this result will hold under any failure probability and investment cost functions–that is, functions replacing Equations (8), (9), and (10) that fulfill the requirements stated in Section 3.1 (e.g., investment costs should be increasing in the reliability or care levels, while the failure probability should be decreasing in these levels).

In summary, we find that the PBC is not necessarily better than the RBC for machine availability and profitability. PBCs can result in a higher failure probability, as shown in Corollary 1, if machine care has a notable impact on machine availability. This is due to the PBC not incentivizing the customer to invest in the care. This result may explain the findings (Kirk and DePalma 2005, GAO 2008, Harada 2010) that there is not enough evidence in the monetary success of the PBC over the

RBC. The profitability depends on both the machine type and how the contracts are designed, as shown in Theorem 1. This answers our first research question. We also find that the total chain profit cannot be maximized by either the RBC or the PBC. By contrast, the FCC leads to first-best failure probability and chain profit by transferring all the failure risk and all the related choices to the supplier, answering our second research question.

5. Behavioral Factors in Service Contracts

In Section 4, we found that the FCC improves the expected supply chain profit compared with the RBC, while the PBC can improve the expected profit compared with the RBC when the reliability has a higher influence than care on the failure probability compared with the care (i.e., $\theta > 0.5$) and/or when investing in reliability is relatively cheaper than investing in care (i.e., $t < k$). However, Harada (2010) suggests that even in this case, the parties in the supply chain might be reluctant to switch from the more commonly used RBC to the more advanced contracts. In this section, we elaborate on potential factors that might explain this behavior and potential deviations from the normative theory.

A prominent behavioral factor is risk, or more precisely risk aversion. Decision makers tend to be risk averse, leading to decisions deviating from expected profit-maximizing predictions (Pratt 1978, Holt and Laury 2002). We discuss this in Section 5.1. In Section 5.2, we discuss other factors affecting decision making, including bounded rationality and mean anchoring. We describe how these behavioral factors can influence decision making in the service contract setting and derive behavioral predictions. In Section 6, we then conduct lab experiments to understand whether those factors affect decisions in our context.

5.1. Risk Preferences

We explain in Section 3 that the customer makes a fixed payment to the supplier as part of each contract (w_{R}, w_{P}, and w_{F}). This amount determines how the total chain profit is shared between the customer and the supplier. It can depend on the bargaining power of the parties, their outside options, and the relationship between them. In addition, this amount often depends on the risk each party faces due to the agreement. Risk preferences affect many decisions in traditional supply chains (Davis et al. 2014, Gurnani et al. 2014, Davis and Hyndman 2019, Becker-Peth et al. 2018, Tüncel et al. 2021) and may also affect the after-sales supply chain performance. Under an RBC, the supplier does not carry any risk, while the customer carries all the breakdown risk. Switching to a PBC or FCC changes this, because then the supplier must carry risk. Depending on the contract and related parameters, suppliers might even take over all the risk. The more risk a company takes, the more it expects to be compensated, a notion referred to as risk premium (Pratt 1978).

A risk-neutral supplier would be indifferent between a risk-free contract (e.g., RBC) and a risky contract (e.g., PBC) when the same expected profit is offered. However, risk preferences will also likely affect the contract choice. Therefore, we assume that a customer wanting to transfer the risk to the supplier by switching from an RBC to either a PBC or an FCC will need to offer the supplier a risk premium (i.e. a higher fixed payment), leading to a higher expected profit for the supplier. We capture the utility value of a payment x by $U(x)$, where $U(x)$ is increasing in x (i.e., $U'(x) > 0$). In Section 3, we introduce expected profits calculations, but not realized profits depending on the actual number of machine breakdowns observed. For ease of notation, we now introduce the expected utility of party $p \in \{\mathrm{s}, \mathrm{c}\}$ (supplier and customer) under contract $m \in \{\mathrm{R}, \mathrm{P}, \mathrm{F}\}$ (RBC, PBC, and FCC) as $\mathbb{E}[U(\Pi_m^p)]$. For any risky payment to a party, there is a certainty equivalent, which is the certain payoff that would give that party equal utility. The difference between the expected payment and the certainty equivalent is the risk premium, r_m^p; thus, we calculate it as

$$r_m^p = \mathbb{E}[\Pi_m^p] - \mathbb{E}[U(\Pi_m^p)]. \tag{11}$$

For example, the supplier will accept switching to an FCC if his expected profit under that contract, $\mathbb{E}[\Pi_{\mathrm{F}}^{\mathrm{s}}]$, is equal to or greater than his risk-free profit under the RBC, $\Pi_{\mathrm{R}}^{\mathrm{s}}$, plus his risk premium to carry the risk under the FCC, $r_{\mathrm{F}}^{\mathrm{s}}$. A supplier with high risk aversion and thus a high risk premium expectation will ask for a high expected payout, thus a high fixed payment, to accept switching to a risky contract. At the same time, a risk averse customer will accept a lower expected payoff when switching from the risky RBC to the risk-free FCC, because she no longer requires a risk premium. For the PBC, this case is somewhat similar, but a bit more complicated, as both parties may face a part of the chain risk.

We can show the conditions under which both parties are willing to switch from the RBC to the PBC or FCC. If the new total profit can be distributed such that the risk premium of the supplier plus his profit under the RBC can be allocated to the supplier, while the customer can acquire her initial certainty equivalent with the FCC or her initial certainty equivalent and new risk premium (in the case of risk sharing) with the PBC, the new contract can result in an agreement. Theorem 2 presents general conditions under which switching to the PBC or FCC is possible.

Theorem 2 *There is a profit allocation that will lead to a switch from the RBC to*
(a) the FCC, if $\mathbb{E}[\Pi_{\mathrm{F}}^{\mathrm{t}}] \geq \mathbb{E}[\Pi_{\mathrm{R}}^{\mathrm{t}}] - r_{\mathrm{R}}^{\mathrm{c}} + r_{\mathrm{F}}^{\mathrm{s}}$*, and*
(b) the PBC, if $\mathbb{E}[\Pi_{\mathrm{P}}^{\mathrm{t}}] \geq \mathbb{E}[\Pi_{\mathrm{R}}^{\mathrm{t}}] - r_{\mathrm{R}}^{\mathrm{c}} + r_{\mathrm{P}}^{\mathrm{c}} + r_{\mathrm{P}}^{\mathrm{s}}$.

On the other hand, Theorem 2 shows that convincing suppliers with higher risk premiums requires higher chain profits, making it more difficult to agree. On the other hand, higher risk premiums on the customer side are likely to make it easier to agree. Therefore, we conclude that supplier and customer risk premiums are imperative to find a contract that will incentivize both parties to change their current contract setting.

In accordance with Theorem 1, total chain profit could be higher under the PBC or FCC than the RBC. If the total chain profit is actually higher with the first two, customers could allocate extra profit to the supplier as the risk premium. However, if the profit difference is not high enough or the supplier is asking for a high risk premium, the customer will need to accept a lower profit to offer the supplier his risk premium. A risk-averse customer (i.e., has $r_{\mathrm{R}}^{\mathrm{c}} > 0$) may accept a profit decrease in exchange for a lower risk. However, if supplier risk premiums under the PBC or FCC are larger than the customer risk premium under the RBC, the parties might not reach an agreement.

Pratt (1978) suggests that the level of the risk premium depends on the risk preference of the decision maker and the level of risk in the payoff. The risk in a payoff is estimated by the magnitude of the variance of the payoff (Pratt 1978). Therefore, the supplier could request different risk premiums under different contracts if profit variances differ between contracts. We provide an analysis of profit variances between contracts in Appendix B, presenting contracts with the highest customer and supplier variance sums. We find that the variance is higher under the FCC than the RBC for a broad range of settings. For such cases, the risk premium requested by a supplier under the FCC ($r_{\mathrm{F}}^{\mathrm{s}}$) will be higher than the customer's initial risk premium under the RBC ($r_{\mathrm{R}}^{\mathrm{c}}$) (assuming a similar level of risk aversion). We can thus conclude that an extra chain profit will be necessary to convince both the supplier and customer to switch to the FCC and that with too high risk-averse suppliers, agreements might not be achieved. The same condition holds when the total variance is higher under the PBC than the RBC.

Overall, we find that the total profit variance under the PBC (with the optimal compensation, v^*) is usually lower than the FCC, because sharing the risk decreases the variance quadratically, making the total profit variance lower. However, the profit increase under the PBC is also smaller than the increase under the FCC (see Theorem 1). Therefore, we argue that the FCC and PBC might not guarantee a contract switch even when a higher chain profit is possible if decision makers are risk-averse. In addition, we cannot conclude whether the switch to the FCC is more or less likely than a switch to the PBC, though the total profit will be higher when switching to the FCC rather than the PBC. To analyze whether the higher chain profit can result in a new contract agreement, we conduct laboratory experiments in Section 6.

In addition to the choice to switch between contracts, risk aversion might affect the decision on the reliability and care effort levels. Risk-averse decision makers will likely choose an effort level that will decrease the variance of their profit. Because the number of broken machines has a binomial distribution, the variance of the profit can be decreased with less effort if the failure probability is higher than 50% and with more effort if the failure probability is lower than 50%. Thus, on the one hand, if the failure probability is already low, exerting more effort will increase the chance that almost no machines will break down. On the other hand, if the failure probability is already high, exerting even less effort will increase the chance that all machines will certainly break down.

5.2. Other Behavioral Factors

In addition to risk preferences, other behavioral factors, such as heuristics and biases, might affect decision making in after-sales supply chains. Some relevant behavioral factors presented in the behavioral supply chain contracting literature are bounded rationality (Su 2008), complexity (Kalkanci et al. 2011), and mean anchoring (Schweitzer and Cachon 2000).

Bounded rationality refers to sub-optimal decisions, and one way to test it is with a random error model (Su 2008). This model assumes that individuals' decisions are a random variable that follows a quantal response equilibrium. In the newsvendor setting, expected order quantities are pulled toward mean demand and order quantities contain noise. Our setting is similar to the newsvendor setting, in which the effort level is the equivalent to the order quantity in the newsvendor setting. As a result, expected effort levels might be pulled toward 50% with boundedly rational decision makers. Moreover, if complexity is an issue, the FCC might bias decision makers to a greater degree than the other contracts, because suppliers make more decisions under the FCC, and therefore the decision task is more complex. Higher complexity might also lead to higher bounded rationality. Furthermore, mean anchoring (Schweitzer and Cachon 2000) would bias decision makers toward the mean effort level. If optimal effort levels are higher than 50%, expected effort levels would be lower while if optimal effort levels are below 50%, expected efforts levels will be higher. Decisions may also adapt toward the optimal over time with learning.

Highlighting different behavioral factors that might affect both effort and contract choice decisions, we follow the lines of behavioral operations management (BOM) research and conduct an experimental study with decision makers to test whether the mentioned behavioral factors are present in our setting. In doing so, we hope to gain insight into how different contracts perform, whether some contracts are more attractive than others, and whether and how PBCs can be implemented successfully.

6. Experimental Study

We analytically found that the FCC will always result in a higher machine availability and chain profit than the RBC, while the PBC might also outperform the RBC depending on the machine type and contract terms. The behavioral factors in the previous section however indicate that these contracts might be prone to biases and non-expected profit-maximizing preferences, such as risk aversion. To test whether decision makers in such a setting are prone to such behavioral factors and if the FCC is able to outperform the PBC, we design and conduct a lab study, to identify and evaluate the actual behavior of decision makers in this setting. In addition, we test whether decision makers are actually willing to switch from the RBC to the PBC or FCC. Such a setting has (to the best of our knowledge) not been investigated before. We explain our experiment setting and treatments in Section 6.1. Afterwards, we present our predictions and hypotheses in Section 6.2 based on our analyses in Sections 4 and 5. After a short summary of the experimental protocol in Section 6.3, we present our results in detail in Section 6.4.

6.1. Setting & Experimental Treatments

We examine a context in which reliability and care have equal impacts in the machine availability and same investment cost (i.e., $\theta = 0.5$ and $t = k$) to avoid a dominance of either care or reliability. To make the setting concrete, we set the machine number to $N = 40$ and the revenue generated by each machine to $R = 7$. The repair cost is $c = 1$, while the customer dis-utility value is $d = 5$ per broken machine. We set the care and reliability investment constants to $k = t = 2.7$ and the lower and upper limits of the failure probability to $p_l = 5\%$ and $p_h = 95\%$, respectively. This leads to an optimal compensation amount of $v^* = 2$ for each broken machine payed by the supplier to the customer under the PBC* (PBC using the optimal $v*$). These parameters result in a setting that mimics the general insights from our analytical study (i.e., higher total profit for the PBC*, which still cannot be as high as the FCC, and a higher profit variance for the FCC). Last, we set the fixed payment, such that the possibility for a negative profit is low, to avoid any potential loss aversion effect on decisions, and expected profits for risky settings are reasonably higher than risk-free settings.

An alternative PBC can be designed by setting $v = d$. For this v, the complete risk shifts to the supplier, who compensates for the full machine breakdown disutility of the customer. In accordance with normative theory, the total chain profit is equal to the RBC in this setting. This contract is of special interest because it is actually identical in profits and risks to the RBC, just by exchanging the roles of customers and suppliers. This contract serves as a reference contract for decision making in the RBC in subsequent analyses. However, performance and effort decision in this contract are not the main focus in our analysis because the contract is dominated by the optimal PBC*. While the risk is shared under the first setting (optimal PBC*) but fully transferred to the supplier in the second setting, we refer the second contract as PBCF (PBC-Full). With the chosen parameters, we show the optimal decisions and outcomes under each contract in Table 1.

We use these contracts to design our treatments. Our experiment contains two parts. In the first part, the decision maker takes the role of the supplier and chooses the related contract parameters for a given contract for 30 periods after 3 periods of warm-up. The supplier sets reliability levels for the

Contract	Reliability	Care	Failure Probability	Chain Profit	Supplier Profit	Customer Profit
PBC*	0.25	0.25	0.725	92.5	46.25	46.25
FCC	0.5	0.5	0.5	106	75	31
PBCF	0.5	0	0.725	79	48	31
RBC	0	0.5	0.725	79	31	48

Table 1 **Optimal effort levels and profits for contracts with experiment parameters**

PBC* (Treatment 1) and PBCF (Treatment 2) and sets both reliability and care levels for the FCC (Treatment 3). Before making a decision, subjects can try different values for both effort levels in all the treatments with a decision support tool and observe the resulting failure probability, their own and the customer's expected profits, the probability distributions of the number of broken machines, and the distribution of their own and the customer's profits. The customer is computerized in Treatment 1 and 2, and sets care levels at expected profit-maximizing levels (Table 1). Subjects are informed about that explicitly. Focusing on supplier decisions, we aim to eliminate social preferences, such as inequality aversion and reciprocity in our experiments, and investigate individual preferences and biases in decision making using service contracts.

At the end of each period, the number of broken machines is randomly generated, and the realized profits of the supplier and customer are calculated accordingly. The machine failure follows a binomial distribution in which the failure probability is determined by effort choices of the supplier and customer. The decision makers are compensated according to their accumulated profit over the 30 periods. This first part enables us to understand how suppliers may perform with each contract. The Online Appendix provides screenshots and instructions.

In the second part of the experiment, decision makers are given 10 sets of contract choices between an RBC and PBC*, PBCF, or FCC (depending on their treatment). This design allows the decision makers to become familiar with the business context and the contract itself (in the first part) before choosing between two contracts. We set the reliability and care levels to optimal values in this part so that decision makers can focus on the contract choice. The goal is to measure the switching point from the RBC to one of the other contracts to which the subject is assigned. The RBC is the same for all 10 contract sets, while the fixed payment (and with that the expected profit) increases for the alternative contract as subjects go down in contract sets. We set the fixed payment for the RBC to 31, which means that the supplier's profit is 31 (and the customer's expected profit is 48; see also the values in Table 1) for all 10 sets. We set the fixed payment values for the PBC*, PBCF, and FCC, such that the first contract choice is between an RBC with 31 certain profit and a risky contract with 31 expected profit, while the last contract choice is between an RBC with 31 certain profit and a risky contract with the highest possible expected profit under the corresponding contract. (Screenshots of the interface are available in the Online Appendix.) Subjects choose between the two contracts for each of the 10 contract pairs, and the reward is determined by their choices in a randomly drawn contract pair. This part enables us to determine whether suppliers are willing to switch from the RBC to a risky contract (PBC or FCC) and how much risk premium is requested to do so. This design is comparable to the risk lottery approach in Holt and Laury (2002).

6.2. Predictions and Hypotheses

Based on the analytical study in Section 4 and the potential behavioral factors described in Section 5 we can derive predictions and hypotheses for our experimental setting.

6.2.1. Effort Levels and Contract Performance With regard to the normative predictions, we find that the FCC achieves the first-best failure probability of 0.5, with reliability and care at first-best levels. Under the PBC*, effort levels are below the first-best, resulting in a higher total failure rate and a lower total chain profit. Total failure rates are the same for the RBC, PBC*, and PBCF. However, given the split of efforts, the total chain profit is higher under the PBC* than it is under the PBCF and RBC (due to the quadratic cost function).

This leads us to our first hypothesis, which predicts the decisions of the supplier and the resulting performances under the PBC*, PBCF, and FCC:

Hypothesis 1 *a. The supplier sets an optimal reliability level, which results in the first-best reliability under the FCC and PBCF and lower reliability under the PBC*.*

b. Failure probabilities are rational, leading to the first-best failure rate for the FCC. Failure rates are higher under both PBCs (being equal for PBC and PBCF) than under the FCC.*

c. The total chain profit is higher for the FCC than both PBCs. It is the lowest under the PBCF.

For the behavioral factors (Section 5), bounded rationality and mean anchoring would both lead to reliability and care levels closer to 50%. This means that boundedly rational decision makers might put too much reliability in the PBC*, while their decisions are not affected in the FCC and PBCF. Moreover, having too high efforts in the PBC* will increase the total chain profit because the failure rate will be closer to the first-best. However, the supplier profit will decrease.

Under the FCC, the supplier makes both the care and reliability decisions. Kalkanci et al. (2011) and Tüncel et al. (2021) find that decision makers deviate from the optimal more as the contract mechanisms get more complex. Under the FCC, a decision maker choosing two contract parameters could face a higher bounded rationality. While average efforts will not be affected (because average efforts are biased toward 50%), higher noise might lead to lower profits. Therefore, efficiency might be worse under the FCC. With regard to the impact of risk on effort levels in our setting, the risk (profit variance) can be decreased with a lower effort than the normative optimum under the PBC* and the PBCF and with a deviation from the optimal in any direction under the FCC.

6.2.2. Contract Choice For our experimental setup, expected supplier profits are higher under each of the three contracts than under the RBC. This means that suppliers should be willing to switch from the RBC to any of the offered contracts when offered to do so. However, the risk aversion levels of the customer and supplier can lead to disagreements in switching from the RBC.

For our setting, under the PBC*, the total profit variance is half the customer's profit variance under the RBC (and only one-quarter of each party, because the breakdown cost is shared equally). This means that the total risk premium requested by the supplier and customer under the PBC* will be half the risk premium requested by the customer under the RBC. Even if the supplier is more risk averse, the total risk premium required to motivate companies to switch to the PBC* might easily be compensated by a higher chain profit attained under the new contract. Therefore, if the supplier and customer have the same risk preference distribution, the agreement possibility with the new contract will be high.

The FCC will attain higher profits for the supplier and the total chain, but the profit variance will also be higher in this setting (see Figure B.1). This might result in a higher risk premium requirement from the supplier, diminishing the superiority of the FCC to convince the companies to change their contractual agreement. Using the experimental method, we analyze the agreement potential of the FCC with actual decision makers. In particular, we examine whether actual risk preferences reduce acceptance of the FCC.

In the PBCF, total profits are equal to the RBC, and rational companies who can agree under the RBC should also be able to agree under the PBCF. The supplier carries the full risk under the PBCF. Therefore, if customers and suppliers have the same risk premium distributions, they will agree to switch their contracts only with a 50% probability (if the supplier is not more risk averse than the customer). Thus:

Hypothesis 2 *A supplier and customer will be more likely to switch from the RBC to the FCC than to the PBC* and PBCF.*

6.3. Experimental Protocol

We designed the interface as a webpage using the MVC (model-view-controller) framework to conduct our experiments online. We conducted the experiments with students attending two large public universities in western Europe, placing 31 students in the PBC* treatment and 30 in the FCC treatment. Because PBCF is only used as a side contract, we only had 24 students participating in that treatment. Participants are first presented with instructions and then they had as much time as they wanted to finish the related treatment. Each treatment took approximately 60 minutes. Participants were rewarded up to 20 euros, including a 4-euro participation fee; the average reward was 16.21 euros.

Table 2 **Efforts, failure probabilities and profits, and tests with normative predictions**

Treatment	Statistic	Optimum	Experiment	
PBC*	τ	25%	31.6%***	(0.08)
	$P(\tau,\kappa)$	72.5%	69.5%***	(0.036)
	$\mathbb{E}[\Pi^{t}]$	92.5	94.00**	(2.58)
	$\mathbb{E}[\Pi^{s}]$	46.25	44.17***	(2.47)
PBCF	τ	50%	53.1%*	(0.094)
	$P(\tau,\kappa)$	72.5%	71.1%*	(0.043)
	$\mathbb{E}[\Pi^{t}]$	79	76.80***	(2.30)
	$\mathbb{E}[\Pi^{s}]$	48	45.80***	(2.30)
FCC	τ	50%	54.3%**	(0.079)
	κ	50%	52.7%*	(0.076)
	$P(\tau,\kappa)$	50%	46.9%**	(0.054)
	$\mathbb{E}[\Pi^{t}]$	106	102.47***	(3.32)
	$\mathbb{E}[\Pi^{s}]$	75	71.47***	(3.32)

Note: Average values are reported with standard deviations in parentheses.
$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

6.4. Results

First, we present the performance of our subjects in the first part of the experiment with regard to the effort, machine failure probability, and resulting profits. Second, we analyze the contract choice behavior.

6.4.1. Efforts, Failure Probability, and Profits Table 2 presents the descriptive statistics of subjects' decisions and related outcomes for the first part of treatments. The average reliability levels under the PBC*, PBCF, and FCC and the care level under the FCC are all above the normative predictions. This results in a lower failure probability (higher machine availability) and lower expected supplier profit with all contracts. While the chain profit under the PBCF and the FCC are also lower than the normative prediction, the reliability choices of subjects result in a higher total chain profit under the PBC*.

Following the behavioral operations literature, we use non-parametric tests to test our hypotheses. Table 2 includes Wilcoxon signed-rank test results comparing experimental outcomes with normative predictions. We find that the average effort levels are significantly above the normative predictions for all contracts ($p < 0.05$ for all). Therefore, subjects deviate from normative predictions in the upward direction for each of the contracts, rejecting Hypothesis 1a. This also means that the reliability levels are above the first-best under the FCC and PBCF. Moreover, we find that the reliability levels under these contracts are significantly higher than the reliability level under the PBC* (Mann-Whitney U tests, $p < 0.001$ for both PBCF vs. PBC* and FCC vs. PBC*).

For the behavioral factors (Section 6.2), we conclude that bounded rationality and mean anchoring cannot explain the consistent too high effort levels among different contracts, as those theories would lead to reliability and care levels closer to 50%. For risk aversion, a supplier can decrease his profit variance by exerting less effort under the PBC* and PBCF, while deviation from any direction from normative optimum will decrease the supplier's profit variance under the FCC. Therefore, risk aversion also cannot explain the consistent too high mean effort.

Testing Hypothesis 1b, we find that the failure probabilities are significantly lower than predicted by normative theory in all contracts ($p < 0.05$ for all), resulting in higher machine availability than predicted. Moreover, in support of Hypothesis 1b, the failure probability under the FCC is significantly lower than the failure probabilities under the PBC* and PBCF (Mann-Whitney U tests, $p < 0.001$ for both FCC vs. PBC* and FCC vs. PBCF).

Testing Hypothesis 1c, we find that total chain profit is significantly higher than it is suggested by normative theory under the PBC*, while it is the lower under the FCC and the PBCF. The reason is that any deviation from the normative optimum for the supplier's reliability choice under the PBCF and the supplier's reliability and care choices under the FCC will decrease the chain profit because these contracts normatively induce first-best effort levels. Therefore, exerting too high effort decreases total profits under these contracts. With regard to the chain profit, the FCC outperforms the PBC* and PBCF, and the PBC* outperforms the PBCF, in support of Hypothesis 1c (Mann-Whitney U tests $p < 0.001$ for FCC vs. PBC*, FCC vs. PBCF, and PBC* vs. PBCF). Nevertheless, when comparing the efficiencies of subjects' decisions (the rate of expected chain profit obtained with decision makers to the optimal chain profit) between the FCC (96.7%) and the PBCF (97.2%), we find no significant difference (Mann-Whitney U tests, $p = 0.492$). This result suggests the complexity is not a significant factor in subjects' decisions in this setting, because behavioral theory would suggest lower efficiency for the FCC due to higher complexity than the PBCF. Overall, we find moderate deviations from normative theory (slightly too high efforts), but the subjects' performance is rather good (supplier efficiency is higher than 95% for all the contracts). As predicted, the FCC increases total profits the most, offering the greatest switching opportunity.

6.4.2. Choosing Contracts While we find that the FCC is still the best contract (by providing the highest profits), there is no guarantee that companies will adopt it when they already have an RBC. Although we find that risk aversion is not a prominent factor in the effort level, it might still be a relevant driver when choosing between different contracts. Investigating different contract mechanisms, Tüncel et al. (2021) note that decision makers have difficulty in understanding the

Table 3 **Supplier's Risk Premium Expectation Statistics**

	$r^{\mathrm{s}}_{\mathrm{P}*}$	$r^{\mathrm{s}}_{\mathrm{PF}}$	$r^{\mathrm{s}}_{\mathrm{F}}$
Mean	10.89	10.00	14.86
Std. Dev.	7.97	8.55	14.50
Zero Premium (%)	6.7%	8.3%	30%
Nonzero Premium (Mean)	11.62	10.91	21.23

consequences of their parameter choices in complex business settings. Therefore, they may not realize the impact of small parameter changes in their profit variances but their risk preferences may affect the contract choices.

Therefore, we analyze the second part of our experiment in more detail to uncover the impact of risk preferences on contract choices. Using the switching point in the 10-choice task, we compute the risk premium that each subject demands for switching from the RBC to the PBC*, PBCF, or FCC. Table 3 presents the mean and standard deviations of the risk premiums. Risk premium values of the supplier are significantly higher than zero (Wilcoxon signed-rank tests, $p < 0.001$ for all contracts). Thus, risk seems to play a role when choosing between contracts. The risk premiums of the supplier under the PBC* and PBCF are close and not significantly different (Mann-Whitney U test, $p = 0.447$). This finding does not match with Pratt (1978), who argues that the risk premium depends on the profit variance. The variance is smaller under the PBC* than under the PBCF (supplier's profit variance under the PBC* is one-quarter of the variance under the PBCF). Moreover, Table 3 shows that the supplier's mean risk premium to accept the switch to the FCC is higher than it is to switch to the PBC* and PBCF. However, the difference is not statistically significant (Mann-Whitney U tests $p > 0.4$ for both comparisons). This is likely because 30% of subjects do not ask for a risk premium under the FCC, while this fraction is only 6.7% and 8.3% under the PBC* and the PBCF, respectively. This means that 30% of the subjects accept switching from the RBC to the FCC without asking for any extra payment to carry the risk. Two proportion z-tests show that the percentages are significantly different ($p = 0.017$ for FCC vs. PBC* and $p = 0.049$ for FCC vs. PBCF). Analyzing (conditional) mean risk premiums for subjects asking for a risk premium, we find that the average nonzero risk premium under the FCC is significantly different from that under the other contracts (Mann-Whitney U test, $p \leq 0.01$ for both comparisons to the PBC* and PBCF). This indicates that a larger fraction of subjects accepts switching to the FCC without asking for a risk premium, but those asking for a risk premium demand a higher premium. Our behavioral study suggested a higher premium because the supplier's profit variance (i.e., risk) is highest under the FCC.

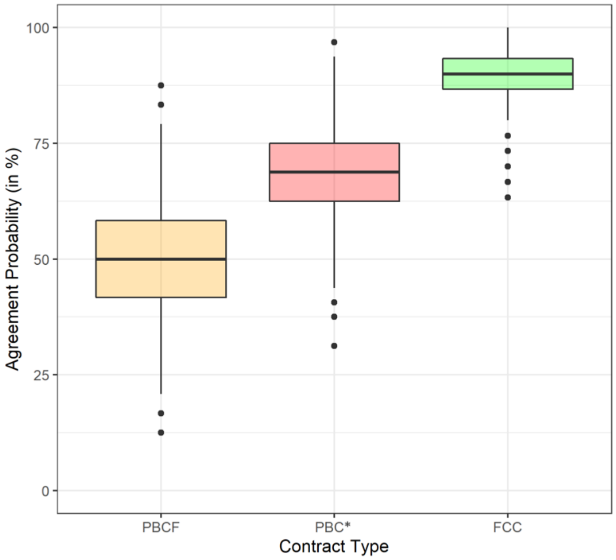

Figure 1 **Agreement probabilities of the customer and the supplier to switch to a new contract**

To estimate how likely each new contract is to actually motivate both companies to agree on switching from the RBC to the new contract, we need to know the additional chain profit under the new contract, the risk premium required by the customer under the RBC, and the risk premiums required by the customer (under the PBC*) and the supplier (under all new contracts). For the analysis, we calculate the additional normative chain profits for each of the new contracts (Table 1). From the second part of our experiment, we sample risk premiums required by the supplier under each of the new contracts. We further sample the risk premiums required by the customer under the RBC from the risk premiums observed for the supplier under the PBCF. We expect these premiums to be representative, because the PBCF and RBC are the same when the customer and supplier roles are switched. Finally, we assume the risk premiums required by the customer under the PBC* to be the same because our analysis does not find significant differences between risk premiums under PBC* and PBCF. In line with the number of subjects in our experiment, we sample 31 times for the supplier for the PBC* contract, 30 times for both the customer and the supplier for the FCC contract, and 24 times for both the customer and the supplier for the PBCF. If the additional chain profit is exactly equal to the additional required risk premiums, we assume an agreement is reached with 50% probability. We calculate for each contract the average agreement probability and repeat this process 10,000 times, leading to the results presented in Figure 1. As a robustness check, we conducted similar analyses using actually achieved profits (instead of normative profits) as presented in Table 2 and drawing customer risk premiums for PBC* from the supplier's PBC* risk premiums. The results are qualitatively similar.

Overall, we find that the FCC attains a higher machine availability and chain efficiency than the PBC and RBC; it also has a high chance of convincing companies to give up the inefficient RBC in favor of the FCC. However, the PBC also has the potential to attain a high agreement probability depending on the business setting. This answers our last research question, and we can conclude that while the FCC can attain the highest chain profit in practice, it may not guarantee a 100% probability of switching from the RBC. Nevertheless, most customers and suppliers will reach to an agreement with an FCC thanks to its high chain profit.

6.4.3. Potential explanations for the observed results We find too high effort levels by suppliers under all contracts. In addition, we find that a significantly higher fraction of subjects accept switching to the FCC without asking for risk premium than with the other contracts. However, those who ask for a risk premium under the FCC ask for a higher premium than that under the PBC* and PBCF. In addition to our formal hypothesis testing, we explore potential reasons for the observed results.

With regard to the too high effort levels, a potential explanation for the upward deviation could be subjects' sustainability concerns. More effort will always decrease the failure probability and increase the machine availability, resulting in a more sustainable business setting. Although the experiment did not include any information to motivate the subjects in this manner, universities train students about sustainability in business, and surveys indicate that people are willing to pay for sustainability (Charter et al. 2002). Analyzing the resulting profits, we find that sustainability concerns might indeed be motivating suppliers to choose actions, decreasing the failure probability even if this choice increases risk and reduces profit. Moreover, too low failure rates under the FCC and PBCF negatively affect the total chain profit.

Regarding the contract choice parts of treatments, the results show that the risk premium values are not significantly different under the PBC* and PBCF. Therefore, the profit variance might not be the most important factor affecting the risk premium requirement of suppliers to bear the risk in after-sales service supply chains. As mentioned previously, we find that more subjects accept switching their contracts without asking for a risk premium under the FCC even when they are taking over a high profit risk. Comparable to the effort choices, potential sustainability concerns might also explain the contract choice behavior. Subjects with high sustainability concerns can have a higher utility value with a contract providing a lower failure probability even if they have to bear more risk. Therefore, additional utility might compensate for the higher risk.

Nevertheless, those subjects who are asking for a risk premium do indeed ask for a higher risk premium under the FCC than under other contracts. This is in line with the higher risk involved under the FCC. In addition, these subjects could consider that making both the reliability and care decisions under the FCC requires a higher premium than the risk premium levels when making only one choice (on reliability) under the PBC. Thus, these subjects may expect additional compensation for doing more under the FCC. This is related to Rosenboim et al. (2013) who find that decision makers who are required to exert more effort in an auction ask for a higher risk premium. Alternatively, Bell (1983) shows that the risk premium requirements can depend on other behavioral preferences, such as people's fear of regret.

7. Conclusion

In this study, we extend the theory on after-sales service contracts to close the gap between theory and practice. We find that while the RBC creates a moral hazard problem on the supplier's side, the PBC results in moral hazard on the customer's side. We thus conclude that both contracts fail to achieve the minimum equipment failure and the first-best solution for the supply chain. By contrast, the FCC allows the supplier to make all the decisions influencing machine availability while also bearing all the consequences, which solves the moral hazard problems and can lead to the first-best solution. Conducting lab experiments with decision makers as suppliers, we find that suppliers choose higher effort levels than our normative prediction for the PBC and FCC. We show that this tendency is not due to risk aversion, bounded rationality, or mean anchoring. Moreover, to understand whether suppliers' risk preferences prevent switching from the RBC to the more efficient PBC and FCC, our experiment elicits the risk premium demanded by suppliers to switch to the PBC and FCC. We find that the likelihood to switch to the FCC is higher than that to switch to the PBC despite the higher risk involved under the FCC.

We find that the customer and supplier collaboration is critical to a better PBC as suggested by Randall et al. (2010) and Hypko et al. (2010), because sharing the risk can lead to higher chain efficiency and better agreement potential under the PBC. Furthermore, the PBC has an additional contract parameter, namely the supplier's compensation amount. While this is automatically provided in our experiments, Harada (2010) and Glas (2020) argue that finding and agreeing on the optimal parameter in a specific business setting can be difficult. As this might be an additional explanation for the subpar PBC performances in practice, future research including human-to-human experiments in which all contract terms are set by decision makers might reveal further insights on the performance of the PBC compared to RBC and FCC.

Despite these limitations, this paper provides valuable insights for managers of companies in after-sales supply chains. Achieving higher machine availability is important for both economical and environmental reasons. While this was initially the problem of customers, PBCs are initiating supplier engagement. As extant literature also highlights, finding the best service contract for the specific business setting is essential for higher efficiency and sustainability. In this study, we provide not only the mechanisms to design the best contract but also insights into risk premium requirements of decision makers to understand whether the best contract is actually feasible for an agreement between chain members. Managers can use our findings to assess the value and feasibility of updating their current contracts or when they are negotiating the contract terms. We recommend that managers wanting a well-designed PBC to consider FCCs, which promise a better chance for a higher efficiency, sustainability and agreement potential, as spotlighted with the design-build-operate-maintain contract in the construction industry (Dahl et al. 2005).

Smith-Gillespie et al. (2018) further highlight the benefits of a contract when the supplier is involved in the operation stage. They show that a supplier with access to information on the performance of his products can provide better customer service and even better equipment design. Moreover, the supplier can follow the equipment throughout its life cycle, thus gaining an opportunity for closed-loop recycling because the supplier can retrieve the high value materials toward the end of the equipment's life cycle. By taking full responsibility of the equipment with the FCC, he can take advantage of the circular economy and maximize the chain's sustainability in addition to its efficiency.

References

Bain & Company. 2015. Winning in industrial service: The hallmarks of a service champion. `https://www.bain.com/insights/winning-in-industrial-service`. Accessed: 2019-09-14.

Becker-Peth, M., U.W. Thonemann. 2018. Behavioral inventory decisions: The newsvendor and other inventory settings. K. Donohue, E. Katok, S. Leider, eds., *The Handbook of Behavioral Operations*, chap. 11. John Wiley & Sons, Ltd, 393–432.

Becker-Peth, Michael, Ulrich W Thonemann, Torsten Gully. 2018. A note on the risk aversion of informed newsvendors. *Journal of the Operational Research Society* **69**(7) 1135–1145.

Bell, David E. 1983. Risk premiums for decision regret. *Management Science* **29**(10) 1156–1166.

Cachon, Gérard P. 2004. The allocation of inventory risk in a supply chain: Push, pull, and advance-purchase discount contracts. *Management Science* **50**(2) 222–238.

Charter, Martin, Ken Peattie, Jacqueline Ottman, Michael J Polonsky. 2002. Marketing and sustainability. *Centre for Business Relationships, Accountability, Sustainability and Society (BRASS) in association with The Centre for Sustainable Design, April* .

Chen, Kay-Yut, Diana Wu. 2018. Buyer-supplier interactions. K. Donohue, E. Katok, S. Leider, eds., *The Handbook of Behavioral Operations*, chap. 11. John Wiley & Sons, Ltd, 459–488.

Cohen, Morris A, Narendra Agrawal, Vipul Agrawal. 2006. Winning in the aftermarket. *Harvard business review* **84**(5) 129–138.

Dahl, Peter, Michael Horman, Teresa Pohlman, Michael Pulaski. 2005. Evaluating design-build-operate-maintain delivery as a tool for sustainability. *Construction Research Congress 2005: Broadening Perspectives*. 1–10.

Davis, Andrew M, Kyle Hyndman. 2019. Multidimensional bargaining and inventory risk in supply chains: An experimental study. *Management Science* **65**(3) 1286–1304.

Davis, Andrew M, Elena Katok, Natalia Santamaría. 2014. Push, pull, or both? a behavioral study of how the allocation of inventory risk affects channel efficiency. *Management Science* **60**(11) 2666–2683.

Donohue, Karen, Özalp Özer, Yanchong Zheng. 2020. Behavioral operations: Past, present, and future. *Manufacturing & Service Operations Management* **22**(1) 191–202.

GAO. 2008. Improved analysis and cost data needed to evaluate the cost-effectiveness of performance-based logistics.

Glas, Andreas H. 2020. Case studies of performance based logistics in the military: International lessons learned. *Necesse* **5**(3) 99–117.

Guajardo, Jose A, Morris A Cohen, Sang-Hyun Kim, Serguei Netessine. 2012. Impact of performance-based contracting on product reliability: An empirical analysis. *Management Science* **58**(5) 961–979.

Gurnani, Haresh, Karthik Ramachandran, Saibal Ray, Yusen Xia. 2014. Ordering behavior under supply risk: An experimental investigation. *Manufacturing & Service Operations Management* **16**(1) 61–75.

Harada, Gaku. 2010. Strategic and operational considerations for the implementation of performance based logistics within the japan maritime self defense force. Master's thesis, Naval Postgraduate School, Monterey, California.

Holt, Charles A, Susan K Laury. 2002. Risk aversion and incentive effects. *American economic review* **92**(5) 1644–1655.

Hou, Jingchen, Andy Neely. 2018. Investigating risks of outcome-based service contracts from a provider's perspective. *International Journal of Production Research* **56**(6) 2103–2115.

Hypko, Phillipp, Meike Tilebein, Ronald Gleich. 2010. Benefits and uncertainties of performance-based contracting in manufacturing industries. *Journal of Service Management* **21**(4) 460.

Kalkanci, Basak, Kay-Yut Chen, Feryal Erhun. 2011. Contract complexity and performance under asymmetric demand information: An experimental evaluation. *Management science* **57**(4) 689–704.

Kim, Sang-Hyun, Morris A Cohen, Serguei Netessine. 2007. Performance contracting in after-sales service supply chains. *Management Science* **53**(12) 1843–1858.

Kim, Sang-Hyun, Morris A Cohen, Serguei Netessine. 2017. Reliability or inventory? an analysis of performance-based contracts for product support services. *Handbook of Information Exchange in Supply Chain Management*. Springer, 65–88.

Kirk, Rebecca L, Thomas J DePalma. 2005. Performance-based logistics contracts: A basic overview. Tech. rep., CNA Corporation Alexandria United States.

Mirzahosseinian, Hassan, Rajesh Piplani. 2011. A study of repairable parts inventory system operating under performance-based contract. *European Journal of Operational Research* **214**(2) 256–261.

Ng, Irene CL, Roger Maull, Nick Yip. 2009. Outcome-based contracts as a driver for systems thinking and service-dominant logic in service science: Evidence from the defence industry. *European management journal* **27**(6) 377–387.

Pratt, John W. 1978. Risk aversion in the small and in the large. *Uncertainty in economics*. Elsevier, 59–79.

Randall, Wesley S, Terrance L Pohlen, Joe B Hanna. 2010. Evolving a theory of performance-based logistics using insights from service dominant logic. *Journal of Business Logistics* **31**(2) 35–61.

Roels, Guillaume, Uday S Karmarkar, Scott Carr. 2010. Contracting for collaborative services. *Management Science* **56**(5) 849–863.

Rosenboim, Mosi, Tal Shavit, Chen Cohen. 2013. Do bidders require a monetary premium for cognitive effort in an auction? *The Journal of Socio-Economics* **42** 99–105.

Schweitzer, Maurice E, Gérard P Cachon. 2000. Decision bias in the newsvendor problem with a known demand distribution: Experimental evidence. *Management Science* **46**(3) 404–420.

Smith-Gillespie, Aleyn, Ana Muñoz, Doug Morwood, Tiphaine Aries. 2018. Rolls-royce: A circular economy business model case. *Universidade de Santiago de Compostela* URL `http://hdl.handle.net/10347/20428`.

Su, Xuanming. 2008. Bounded rationality in newsvendor models. *Manufacturing & Service Operations Management* **10**(4) 566–589.

Tüncel, Özge, Niyazi Taneri, Sameer Hasija. 2021. Why are minimum order quantity contracts popular in practice? a behavioral investigation. *Manufacturing & Service Operations Management* **accepted for publication**.

Vanderlande. 2020. An example of vanderlande's performance based contract with operation. URL `https://www.vanderlande.com/references/istanbul-airport/`.

Appendix A Proofs

A.1 Proof of Lemma 1

Under the RBC, to optimize his (expected) profit, the supplier should maximize Equation (2) toward τ, implying that he should minimize the investment in reliability (i.e., $\tau_{\mathrm{R}}^* = 0$).

Under the PBC, to optimize his expected profit, the supplier should maximize Equation (4) toward τ. As $T'(\tau) = 2t\tau N$ (see Equation (9)) and $\frac{\partial P(\tau,\kappa)}{\partial \tau} = -\theta(p_h - p_l)$ (see Equation (8)), the supplier should set the reliability level such that $-(c+v)\theta(p_h - p_l)N + 2t\tau N = 0$ (if possible); that is, $\tau_{\mathrm{P}}^* = \min\left[\frac{(v+c)\theta(p_h-p_l)}{2t}, 1\right] > 0$.

Under the FCC, to optimize his expected profit, the supplier should maximize Equation (6) toward τ. With a similar reasoning as that under the PBC, this implies that $\tau_{\mathrm{F}}^* = \min\left[\frac{(d+c)\theta(p_h-p_l)}{2t}, 1\right]$. As $d \geq v$, we have $\tau_{\mathrm{F}}^* \geq \tau_{\mathrm{P}}^*$.

The first-best reliability level comes from maximizing Equation (1) toward τ. We can easily show that the partial derivative of this expected profit function is identical to that of Equation (6), the expected profit function of the supplier under FCC, such that $\tau^* = \tau^*_{\mathrm{F}}$

As we assume that $\tau^* < 1$, our proof is complete.

A.2 Proof of Lemma 2

Under the RBC, to optimize her (expected) profit, the customer should maximize Equation (3) toward κ. As $K'(\kappa) = 2k\kappa N$ (see Equation (10)) and $\frac{\partial P(\tau,\kappa)}{\partial \kappa} = -(1-\theta)(p_h - p_l)$ (see Equation (8)), the customer should set the care level such that $-(d+c)(1-\theta)(p_h-p_l)N + 2k\kappa N = 0$ (if possible); that is, $\kappa^*_{\mathrm{R}} = \min\left[\frac{(d+c)(1-\theta)(p_h-p_l)}{2k}, 1\right]$.

Under the PBC, to optimize her (expected) profit, the customer should maximize Equation (5) toward κ. With a similar reasoning as that under the RBC, this implies that $\kappa^*_{\mathrm{P}} = \min\left[\frac{(d-v)(1-\theta)(p_h-p_l)}{2k}, 1\right]$. As $d + c > d - v$, we have $\kappa^*_{\mathrm{R}} \geq \kappa^*_{\mathrm{P}}$ (with equality only if $\kappa^*_{\mathrm{R}} = \kappa^*_{\mathrm{P}} = 1$). If $d = v$, then $\kappa^*_{\mathrm{P}} = 0$.

Under the FCC, to optimize his (expected) profit, the supplier should maximize Equation (7) toward κ. Doing so gives the same result as for the customer under the RBC; that is, $\kappa^*_{\mathrm{F}} = \min\left[\frac{(d+c)(1-\theta)(p_h-p_l)}{2k}, 1\right]$.

The first-best care level comes from maximizing Equation (1) toward κ. We can easily seen that the partial derivative of this expected profit function is identical to that of Equation (3), the expected profit function of the customer under RBC, such that $\kappa^* = \kappa^*_{\mathrm{R}} = \kappa^*_{\mathrm{F}}$.

As we assume that $\kappa^* > 1$, our proof is complete.

A.3 Proof of Corollary 1

The failure probability, given in Equation (8), is decreasing in both the reliability level τ and the care level κ. The results on the reliability levels that we use come from Lemma 1, and results on the care levels come from Lemma 2.

As $\tau^*_{\mathrm{F}} > \tau^*_{\mathrm{R}}$ and $\kappa^*_{\mathrm{F}} = \kappa^*_{\mathrm{R}}$, part (a) holds.

As $\tau^*_{\mathrm{F}} > \tau^*_{\mathrm{P}}$ and $\kappa^*_{\mathrm{F}} > \kappa^*_{\mathrm{P}}$, part (b) holds.

As $\tau^* = \tau^*_{\mathrm{F}}$ and $\kappa^* = \kappa^*_{\mathrm{F}}$, part (c) holds.

We can calculate the failure probabilities under the PBC and RBC by setting the corresponding reliability and care levels, given in Lemmas 1 and 2, in Equation (8). Then

$$P(\tau^*_{\mathrm{P}}, \kappa^*_{\mathrm{P}}) = p_h - \frac{(c+v)\theta^2(p_h-p_l)^2}{2t} - \frac{(d-v)(1-\theta)^2(p_h-p_l)^2}{2k}, \text{ and}$$
$$P(\tau^*_{\mathrm{R}}, \kappa^*_{\mathrm{R}}) = p_h - \frac{(d+c)(1-\theta)^2(p_h-p_l)^2}{2k},$$

such that $P(\tau^*_{\mathrm{R}}, \kappa^*_{\mathrm{R}}) - P(\tau^*_{\mathrm{P}}, \kappa^*_{\mathrm{P}}) = (c+v)(p_h-p_l)^2\left(\frac{\theta^2}{2t} - \frac{(1-\theta)^2}{2k}\right)$. This implies that part (d) holds.

A.4 Proof of Theorem 1

We can calculate the expected total chain profits under the various contracts by setting the corresponding reliability and care levels, given in Lemmas 1 and 2, in Equation (1). Then

$$\mathbb{E}[\Pi^{\mathrm{t}}(\tau^*_{\mathrm{R}},\kappa^*_{\mathrm{R}})] = RN - p_h(d+c)N + (p_h-p_l)^2N(d+c)^2\frac{(1-\theta)^2}{4k},$$
$$\mathbb{E}[\Pi^{\mathrm{t}}(\tau^*_{\mathrm{P}},\kappa^*_{\mathrm{P}})] = RN - p_h(d+c)N + (p_h-p_l)^2N\left[\frac{(2d-v+c)(c+v)\theta^2}{4t}+\frac{(d+v+2c)(d-v)(1-\theta)^2}{4k}\right], \text{ and}$$
$$\mathbb{E}[\Pi^{\mathrm{t}}(\tau^*_{\mathrm{F}},\kappa^*_{\mathrm{F}})] = RN - p_h(d+c)N + (p_h-p_l)^2N(d+c)^2\left[\frac{\theta^2}{4t}+\frac{(1-\theta)^2}{4k}\right].$$

Since $\frac{\theta^2}{4t} > 0$, we see that part (a) holds.

Since $v \le d$, we see that $(2d-v+c)(c+v) \le (d+c)^2$ and $(d+v+2c)(d-v) < (d+c)^2$; thus, part (b) holds.

Since $\tau^* = \tau^*_{\mathrm{F}}$ and $\kappa^* = \kappa^*_{\mathrm{F}}$, part (c) holds.

Next, $\mathbb{E}[\Pi^{\mathrm{t}}(\tau^*_{\mathrm{R}},\kappa^*_{\mathrm{R}})] - \mathbb{E}[\Pi^{\mathrm{t}}(\tau^*_{\mathrm{P}},\kappa^*_{\mathrm{P}})] = (c+v)(p_h-p_l)^2N\left(\frac{(c+v)(1-\theta)^2}{4k}-\frac{(2d-v+c)\theta^2}{4t}\right)$. This implies that part (d) holds.

We derive $\frac{d\mathbb{E}[\Pi^{\mathrm{t}}(\tau^*_{\mathrm{P}},\kappa^*_{\mathrm{P}})]}{dv} = \left[\frac{(d-v)\theta^2}{2t}-\frac{(v+c)(1-\theta)^2}{2k}\right](p_h-p_l)^2N$. Setting this equal to 0 shows that part (e) holds.

A.5 Proof of Theorem 2

To switch from the RBC to another contract, both the customer and the supplier should have an (expected) utility value under the new contract that is greater than or equal to the (expected) utility value under the RBC. The expected utility values under contract m for the supplier and customer are equal to the expected profit minus the risk premium, $\mathbb{E}[\Pi^{\mathrm{s}}_m] - r^{\mathrm{s}}_m$ and $\mathbb{E}[\Pi^{\mathrm{c}}_m] - r^{\mathrm{c}}_m$, respectively. Note that under the RBC, the supplier has a risk-free profit, so that the expected profit is a deterministic profit and the risk premium is 0, while under the FCC, the customer has a risk-free profit.

This means that both the supplier and the customer want to switch (or are indifferent to switching) from the RBC to the FCC if $\Pi^{\mathrm{s}}_{\mathrm{R}} \le \mathbb{E}[\Pi^{\mathrm{s}}_{\mathrm{F}}] - r^{\mathrm{s}}_{\mathrm{F}}$ and $\mathbb{E}[\Pi^{\mathrm{c}}_{\mathrm{R}}] - r^{\mathrm{c}}_{\mathrm{R}} \le \Pi^{\mathrm{c}}_{\mathrm{F}}$. By summing both left-hand sides and both right-hand sides, and when $\mathbb{E}[\Pi^{\mathrm{t}}_m] = \mathbb{E}[\Pi^{\mathrm{c}}_m] + \mathbb{E}[\Pi^{\mathrm{s}}_m]$, we show that it is possible to find an allocation that makes both the supplier and the customer want to switch (or be indifferent to switching) from the RBC to the FCC if $\Pi^{\mathrm{s}}_{\mathrm{R}} + \mathbb{E}[\Pi^{\mathrm{c}}_{\mathrm{R}}] - r^{\mathrm{c}}_{\mathrm{R}} \le \mathbb{E}[\Pi^{\mathrm{s}}_{\mathrm{F}}] - r^{\mathrm{s}}_{\mathrm{F}} + \Pi^{\mathrm{c}}_{\mathrm{F}}$ or if $\mathbb{E}[\Pi^{\mathrm{t}}_{\mathrm{R}}] - r^{\mathrm{c}}_{\mathrm{R}} \le \mathbb{E}[\Pi^{\mathrm{t}}_{\mathrm{F}}] - r^{\mathrm{s}}_{\mathrm{F}}$, which proves part (a).

Similarly, both the supplier and the customer want to switch from the RBC to the PBC if $\Pi^{\mathrm{s}}_{\mathrm{R}} \le \mathbb{E}[\Pi^{\mathrm{s}}_{\mathrm{P}}] - r^{\mathrm{s}}_{\mathrm{P}}$ and $\mathbb{E}[\Pi^{\mathrm{c}}_{\mathrm{R}}] - r^{\mathrm{c}}_{\mathrm{R}} \le \mathbb{E}[\Pi^{\mathrm{c}}_{\mathrm{P}}] - r^{\mathrm{c}}_{\mathrm{P}}$. With a similar reasoning as before, this leads to the proof of part (b).

Appendix B Variance Analysis

Figure B.1 presents the contracts with the highest variance totals in different business settings. The disutility, d, the repair cost, c, the reliability investment constant, t, and the probability limits, (p_l, p_h), are fixed as 5, 1, 1 and (0.00001, 0.99999) respectively. Moreover, the compensation amount under the PBC, v, is set to the optimal as given in Corollary 1. While increasing the reliability investment constant and shrinking the probability range extends regions where either the PBC or the FCC has the highest total variance, the FCC regions extend more. The change in the rate of disutility to the repair cost shrinks the FCC region and extends the RBC region. Last, setting the compensation amount equal to the disutility, which results in the worst chain profit performance with the PBC, extends the PBC region.

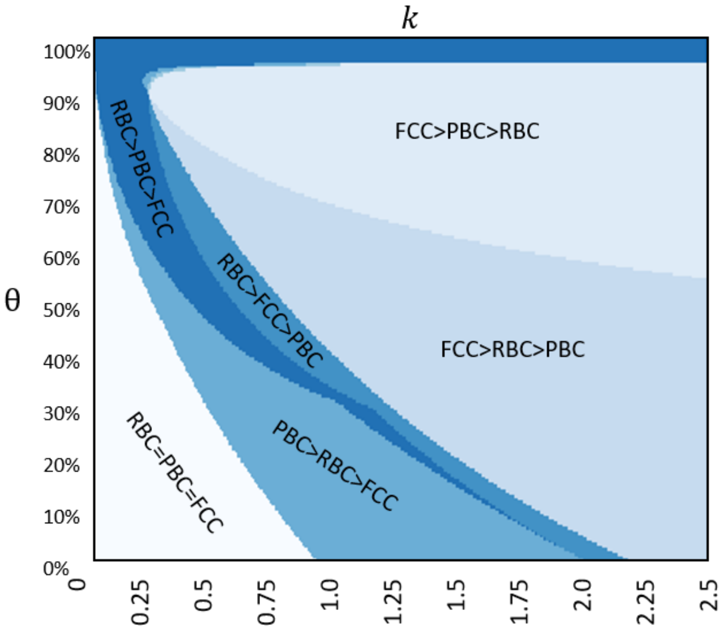

Figure B.1 **Contracts with the highest variance totals for the customer and supplier**