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Product Service System Availability Improvement through Field Repair Kit Optimization: A Case Study †

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Abstract: Product service system (PSS) is becoming a popular business model, where companies offer product based service to customers to realize steady recurring revenue. However, to provide PSS-based service to customers in reliable way, PSS need to be supplemented with a field repair kit onsite, in case of parts failure and PSS shutdown. The field repair kit consists of frequently used spare parts in multiple quantities. However, mismatch in spare parts type and quantities in the field repair kit will results in sub-par performance of PSS for both customer and company. In this paper, a case study involving industrial PSS repair kit optimization is presented. In the case study, the field repair kit for complex industrial printing system is cost optimized, while satisfying the system availability requirement, specified by the maintenance contract between the company and the customer. Key analysis steps and results are presented to offer insight into the PSS field repair kit optimization, offering useful references to industrial practitioners.

Keywords: product service system (PSS); availability; field repair kit

1. Introduction

Research on the product service system (PSS) [1,2] is increasing as many leading global industries are shifting their focus toward product based services. For example, in the aircraft engine industry, the old business model aimed to sell an engine to an aircraft manufacturer and provide engine maintenance, if necessary. Over time, this business model has evolved into a service centric model, often called the "power by the hour" approach [3], where aircraft engine companies own the engines installed on customer's aircrafts, and charge their customers for actual flight hours. This paradigm shift impacted many facets of product development and lifecycle management, including product requirement definition, subsystem design, service development, and total product lifecycle cost analysis.

According to general literature survey by Beuren [1], academia defines PSS as "a combination of products and services in a system that provides functionality for consumers and reduces environmental impact" [4]. Similarly, Baines et al. [5] defined PSS as "an integrated product and service offering that delivers value in use to the customer". Tukker [6] further categorized PSS into eight different types, which are clustered into product-related services, use-oriented services, and result-oriented services. The PSS presented in our case study is the product-related service type, whose company offers a product and related services (e.g., financing, maintenance contract, spare and consumable parts supply) throughout the lifecycle of the product.

There are four different essential elements in the PSS: product, process, related human role, and service. Product typically consists of actual hardware equipment used to provide specific functions required. Process is the sequence of actions required to provide the desired service. A related human role consists of activities that need to be performed by personnel who are part of the PSS. Finally, the service is the output of all these equipment and activities that is provided to customers. One such example of PSS is an amusement park ride. The product is the park ride itself, which is necessary for providing necessary entertainment service to ride users. The process is a sequence of activities necessary to provide ride service, which consists of getting customers into the ride, operating the ride equipment, getting customers out of the ride, and equipment maintenance. Related human role include operating and maintaining ride equipment. The service aspect is the ride experience itself, enjoyed by customers.

For PSS, one of the key performance metrics is the system availability. The PSS must be operational to meet the availability requirement promised to customers. For the amusement park ride example previously mentioned, the ride apparatus must be operational during park business hours to provide customers with a satisfactory ride experience. Not meeting this availability requirement, due to ride apparatus failure, will result in loss of customers and revenue. One way to maximize the uptime availability of the PSS is to keep a field repair kit, consisting of spare parts for the PSS, on the customer site, in case of such a failure. In many cases, product design teams rely on their prior experiences to determine the types and quantities of spare parts in field repair kits. However, this often result in a sub-optimal field repair kit, containing some spare parts that are never used, or carrying less-than-necessary quantities of some spare parts that are always used. This mismatch of spare parts inventory may cause unacceptable downtime and lost revenue for PSS customers and providing companies.

In this paper, a PSS field repair kit optimization case study is presented in detail. In the case study, a field repair kit for a complex PSS (industrial printing system) was optimized in terms of field inventory kit cost, while satisfying the availability requirement set by contract with the customer. A high fidelity simulation PSS simulation model was created to simulate spare parts usage during the PSS operation. Using the model, a cost optimal field repair kit was identified. Subsequent analysis was performed to determine the confidence level that the PSS is capable of achieving the imposed PSS availability requirement. The paper is organized as follows. A survey of related research literature is presented in Section 2. The case study overview, optimization process, analysis of the results, and discussion are presented in Section 3. The paper closes with conclusions in Section 4.

2. Literature Review

Traditionally, product manufacturers have focused their primary efforts on product development and sales. For these traditional manufacturing firms, the term "service" consisted of maintenance and repair of their products in the field as needed. However, as companies seek ways to create recurring revenues throughout the lifecycle of their products, the trend to integrate the product with the services offered to the customer has increased. This approach has advantage of continuous and stable revenue generation for the company because it establishes a long term relationship between the company and the customer [7], as well as sustaining environment from the social and company perspectives [8,9]. There have been successful examples of such practices, which include Gage Products and PPG Industries [10], where companies have integrated their core products with the total service offered to the customer. For example, major printing systems manufacturing companies, such as Xerox and HP, offers total document management services to various customers to optimize their total document production workflows.

Once the PSS is deployed in the field, it is of critical importance that the deployed PSS is operational, meeting the contracted availability requirement promised to the customer. One way to meet the availability requirement is through implementing appropriate maintenance policy, which includes preventive maintenance and predictive maintenance. There have been several works published in the field of preventive maintenance and predictive maintenance. Relevant works on preventive maintenance include work by Adhikary et al. [11], who proposed multi-objective genetic algorithm approach to optimize availability and maintenance cost through preventive maintenance scheduling model, work by Moghaddam [12], who proposed a nonlinear mixed-integer optimization model for a manufacturing system, and the work by Mokhtar et al. [13], who proposed a maintenance policy optimization framework using Bayesian networks. Additionally, related works on predictive maintenance include work by Van Horenbeek and Pintelon [14], who proposed a dynamic predictive maintenance policy and compared it with other various maintenance policies to show that the proposed policy results in significant cost reduction. Another work by Wang et al. [15] proposed cloud-based predictive maintenance paradigm to advance the state of intelligent manufacturing. Finally, there is a research trend that aims to link big data to improve predictive maintenance [16,17].

Another way to achieve required PSS availability is through implementing component redundancy and keeping an onsite spare parts field repair kit, consists of parts that are expected to fail [18]. This will prevent the unintended PSS downtime due to lack of critical spare parts. However, deciding on the quantity of each spare part of the PSS field repair kit requires information on the total PSS life cycle, average usage per designated period, and individual spare part's reliability. The management of spare parts inventory is a well-developed research topic. Published works have investigated topics such as the allocation of spare parts inventory within a multi-echelon supply chain [19–21], spare parts inventory and reliability decision framework with service constraints [22,23], combined optimization of preventive maintenance and spare parts inventory [24,25], and obsolescence management [26]. Recent advances in PSS-related research has expanded to other important areas, such as sustainable product service system design [27,28], cloud based product service system design [29,30], product service system implementation for the smart city [31], and incorporation of digital twin concept to the product service systems [32]. Recent works on field repair kit optimization include the joint planning and optimization of spare parts inventory and service engineer staffing [33,34].

In this paper, the featured case study focuses on the cost optimization of the onsite spare parts repair kit, subject to the PSS availability requirement specified by the contract between the company and the customer. Once the field repair kit is optimized for a specific level of availability requirement, additional analysis will determine the level of confidence of the PSS in meeting the availability requirement with the repair kit. The work presented in this study contributes to existing literature by introducing a real industry PSS case study that can serve as a reference for other industry practitioners.

3. Product Service System Case Study

3.1. Case Study Overview

Xerox, one of the world's leading printing system manufacturers, has a fleet of industrial printing systems deployed in the field. Industrial printing systems are installed at customer's print shops, where they become part of production systems to produce printing goods, which, in turn, are sold to their customers. Xerox (the company) and the customer typically have a recurring fee based maintenance contracts, in which the company maintains customer's printing system on regular basis, supplies necessary consumable parts required for operation, and performs repairs in case of printing system failure. Usually, as part of the maintenance contract, the company is responsible to have its printing system available for production above a certain agreed threshold during the regular operating hours. Failure by the company to meet the contracted system availability requirement may result in penalty to the company, or even worse, cancellation of the maintenance contract by the customer. In that sense, the industrial printing system can be classified as a PSS for Xerox, and will be referred to as such in subsequent sections.

Since unexpected system failures are inevitable, the company supplies customers with a field repair kit, consists of frequently replaced spare parts. Typically, the composition of the spare parts and the quantity of each spare part in the field repair kit are determined by printing system design team, based on historical performance of similar parts in other previously launched products. After the product launch, the composition and quantities of spare parts in the field repair kit are updated as the true life of spare parts become known.

However, on many occasions, this result in a sub-optimal field repair kit, where some parts are never used due to less than expected parts failure, while some parts are in constant shortage and demand as they are used more frequently than expected. This mismatch creates an undesirable situation for both the company and customers. Customers experience more unexpected PSS downtimes, above the threshold established by the maintenance contract, due to a shortage of critical spare parts. This will impact a customer's ability to meet their business goals. As for the company, mismatch in field repair kit spare parts type and quantity may result in their failure to meet the availability requirement promised to the customer, jeopardizing their credibility, and sometimes terminating their contract with that particular customer. Another issue concerns the field repair kit inventory itself. In some cases, the company financially owns the field repair kit inventory, tying up corporate capital in the form of spare parts inventory. If some spare parts become obsolete while in a company's possession, the company would incur unnecessary financial loss due to the extra cash that was tied up in the form of unused parts, and the additional cost for management of obsolete parts. The constant shortage of some spare parts can create an extra cost issue in terms of expedited shipment from parts suppliers and to customer's sites. In this case study, a simulation based optimization framework was created and utilized to configure a cost-optimal PSS field repair kit to satisfy the specific availability requirements. One of several industrial printing system produced by the company was used as a specific example.

To optimize the PSS field repair kit and to perform further analysis, following steps were followed. First, a high fidelity PSS simulation model was created to simulate the system operation and availability, subject to spare parts failure. Next, using the simulation model, a series of key parameter variation experiments were conducted to yield PSS availability under specific parameter settings. The obtained results were used to construct a regression based PSS availability model that would describe PSS availability as the function of key parameters. Regression model was then used to optimize the field repair kit in terms of the inventory cost, while satisfying the availability requirement. Finally, a Monte Carlo simulation of PSS with the optimized field repair kit was performed to estimate the confidence level for the PSS to meet the specific availability requirement.

3.2. *Case Study Assumptions*

Several assumptions were made to establish the boundary within which the case study is valid, and to reflect reality. Simulations, subsequent optimizations, and analysis were performed within the framework of the assumptions.

• Definition of availability: in this case study, the availability of the PSS is defined as follows. When the PSS shuts down due to a spare part failure, the part is replaced with a fresh part from the field repair kit. If there is no replacement part present in the field repair kit inventory, it must be shipped from the central warehouse. This is recorded as a PSS down incident. The availability metric is the percentage of all PSS part requests that is fulfilled by immediate replenishment from the field repair kit. For example, if there were 100 requests for various spare parts, and 95 of them were fulfilled from the field repair kit without placing emergency order from the central warehouse, the availability of the PSS is 95%.

• PSS and production system configuration: for the case study, the production system consists of two PSSs of the same type in a serial configuration. The field repair kit optimized in the case study is configured to service both PSSs.

• Field repair kit spare parts composition and quantities: the design team provided the list of spare parts in the field repair kit, along with their respective quantities and the estimated life. For the case study, all parts identified by the design team were included in the optimization. A total of 55 spare parts were included in the field repair kit.

• Periodic PSS usage: the PSS usage is defined as the number of prints produced per time period (month in this case study). For the case study, the nominal usage is set to 8.0 million, as provided by the design team responsible. The usage data was derived from past historical data of customers who have used similar type of PSS. Additionally, it was assumed that all spare parts fail based on PSS usage, not based on time.

• Onsite conditions: availability of PSS also depends on other aspects, such as experience of PSS operation and maintenance staff and production equilibrium. It was assumed that the level of expertise of operation and maintenance staff was competent to upkeep the PSS at the desired performance level, as it typically is for real onsite facilities. Additionally, it was assumed that the production equilibrium is maintained.

• Simulation assumption: for the Monte Carlo simulation, spare parts life distribution and periodic PSS usage distribution were provided by the design team. Additionally, simulation time was set to be equal to the typical contract term agreed between the company and the customer. For this case study, the contract term was set to five years, with a single simulation period equal to one month.

3.3. Product Service System Simulation Model

The first step in the proposed process is to create a high fidelity PSS model. The Anylogic™, software was used to create the PSS model to simulate PSS usage and usage-based spare parts failures. Figure 1 shows the basic structure of the PSS discrete event simulation model. The PSS selected for the case study is typically sold in pairs (quantities of two) to customers, and used in serial configuration to process customer orders for the duration of the contract period. There are work in process (WIP) product inventory as shown in the model. When the simulation starts, document orders start to arrive into the facility. Each order contains a request for certain quantities of a finished product, which, in this case, is the document produced in the desired quantity. The production line initiates product manufacturing, and utilizes the PSS that is part of the total production system. Once requested product quantity is manufactured, the order is complete and the finished document products are processed for delivery to final recipients. The simulation model records PSS usage, which is equal to the total quantity of the products manufactured. When the PSS usage reaches a threshold for a particular spare part with a specific usage based failure rate, the part fails, and the PSS shuts down. The failed part is replaced with the part from the field repair kit inventory. Once the spare part is replaced, the usage count for that specific spare part is reset and the production resumes. The replaced part is replenished from the central warehouse to fill the field repair kit. If the failed part is out of stock at the customer's site, then an emergency order is placed, and the part is shipped from the central warehouse immediately, using one-day express shipment. When this happens, it is recorded as a down incident for the PSS.

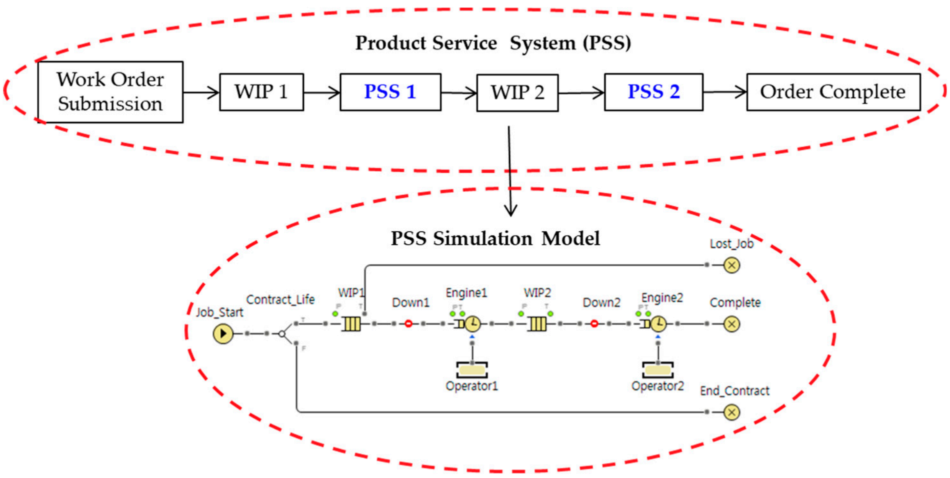

Figure 1. Simulation model flow chart for industrial printing product service system.

Figure 2 shows the Input-Process-Output (IPO) diagram for the PSS simulation model shown in Figure 1. Required input data are spare part life, quantity of spare part onsite and the monthly usage of PSS. Once the simulation ends, the model yields three specific outputs: (1) total demand for the spare part required by PSS, (2) the total number of PSS down incidents due to spare part shortage, and (3) the PSS availability.

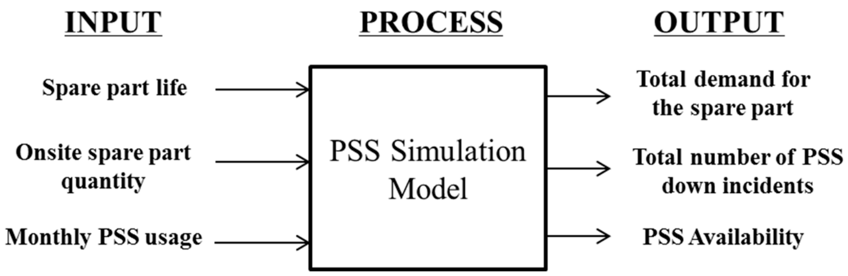

Figure 2. Input-Process-Output (IPO) diagram of the simulation model.

3.4. PSS Availability Model

The second step in the overall process is to construct the PSS availability regression model by performing key parameter variation experiments for PSS using the simulation model. A model of PSS availability as a function of input parameters shown in Figure 2 is created. Table 1 shows the key parameters and ranges of the parameter values used for the case study.

To create a reliable model, 240 different experiment runs were set up and performed using different deterministic parameter values, and resulting PSS availability values were recorded. Table 2 shows results of the 15 deterministic experiment runs out of 240 runs performed. For example, experiment number 2 in Table 2 shows a spare part with a life of 10 million uses (0.1 failure per million use), with only one provided in the field repair kit. When the simulation was performed with PSS monthly usage of 10.2 million, the availability of the PSS overall was 15% due to shortage of the part. Availability for each run was recorded. Once all experiment runs are complete, a regression based PSS availability model was constructed using parameters shown in Table 1. The regression model provides a good surrogate means to calculate PSS availability using spare part failure rate, onsite spare part quantity, and PSS usage per period. One thing to note is that the regression model is valid within parameter value ranges shown in Table 1.

Table 1. Key parameters and their value ranges for simulation and optimization.

Parameters	Values Ranges
Spare part failure rate (1/spare part life)	0.001–0.5 failures per million prints
Onsite spare part quantity	0–10
PSS usage per unit period	5.7–10.2 million prints

Table 2. Partial results of deterministic PSS simulation.

Runs	Spare Part Failure Rate (per Million Prints)	Quantity in the Field Repair Kit	PSS Availability based on Monthly PSS Usage		
			5.7 million	8.0 million	10.2 million
1	0.032	2	100%	100%	78%
2	0.100	1	50%	50%	15%
3	0.100	5	100%	100%	56%
4	0.500	2	100%	100%	80%
5	0.500	10	100%	100%	88%

3.5. Cost Optimization Model

For the next step of the process, the PSS availability regression model created from the previous step is embedded into the field repair kit cost optimization model. The IPO diagram for the optimization model is shown in Figure 3.

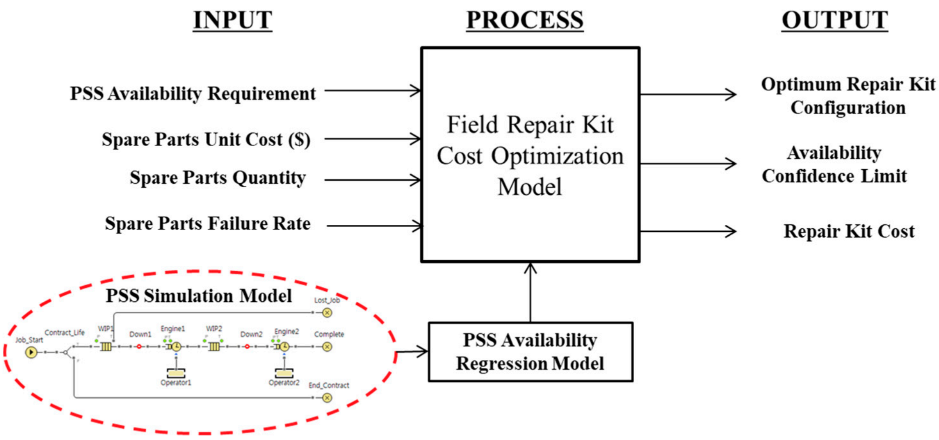

Figure 3. IPO diagram of the field repair kit cost optimization model.

For the field repair kit cost optimization, several input parameters are required. The first parameter is the required PSS availability target. This is typically dictated by the customer who utilizes the PSS when the maintenance contract is signed. The second parameter is the unit cost for each spare part in the field repair kit. The third parameter is the quantity of each spare part in the field repair kit, and the last parameter is the failure rate of each spare part. Table 3 shows a partial list of the actual spare parts included in the field repair kit, with actual parameter values. It should be noted that the unit cost of each spare part is added, since the objective of the optimization is to minimize the total cost of the field repair kit. For the monthly PSS usage, it was set at 8.0 million, based on field data for similar systems. Optimization was performed using spreadsheet-based commercial software (QuantumXL™), which uses a heuristic algorithm.

Table 3. Partial list of spare parts and quantities in the PSS field repair kit originally proposed by the design team.

Spare Part	Unit Cost (Normalized)	Original Part Quantity in the Field Repair Kit	Failure Rate (per Million Prints)
A	100.00	2	0.033
B	2.89	1	0.040
C	1.23	1	0.035
D	0.78	6	0.500
E	0.77	1	0.035
F	0.29	2	0.033
G	0.19	1	0.050
H	0.17	4	0.056
I	0.05	4	0.040
J	0.03	4	0.056
K	0.01	2	0.500

For the optimization, three different scenarios were formulated after discussion with the design team. Table 4 lists proposed scenarios. The first scenario serves as the base scenario, where the PSS operates with the original field repair kit composition shown in Table 3. In the second scenario, the PSS availability requirement parameter is set to 95%, and the field repair kit is optimized for total cost. For the third scenario, the PSS availability requirement parameter is relaxed to 90%.

Table 4. Key parameters and their value ranges for simulation and optimization.

Scenario	Scenario Description
1: Base	PSS field repair kit composition is provided by the PSS design team.
2: 95% availability	PSS field repair kit is cost optimized with PSS availability requirement set to 95%.
3: 90% availability	PSS field repair kit is cost optimized with PSS availability requirement set to 90%.

3.6. Optimization Results and Discussion

Table 5 shows a partial list of the optimized field repair kit spare parts shown in Table 3. The list for scenario 1 shows the original quantities of spare parts proposed by the design team. Second column shows the optimized spare parts list for 95% availability requirement. The last column shows a partial list of spare parts, optimized for 90% availability requirement. Observation of the list reveals some key insights. In the original repair kit composition, two units of spare part A were kept on the customer site. However, the optimum composition eliminated spare part A altogether from the field repair kit, mainly because of the part unit cost, which was significantly higher than the cost of any other part in the field repair kit. On the other hand, part J, which has a very low part unit cost, saw an increase in quantity from the original quantity proposed by the design team. The observation of the optimization results is that in balancing the field repair kit cost and the availability requirement, the optimized field repair kit is composed in a way that the PSS will only shut down for a part that is too expensive to be held onsite, and not for a low cost part.

Table 5. Partial list of spare parts and their quantities in the optimized field repair kit for each scenario.

Spare Part	Unit Cost (Normalized)	Spare Parts Quantity		
		Scenario 1	Scenario 2	Scenario 3
A	100.00	2	0	0
B	2.89	1	5	4
C	1.23	1	12	4
D	0.78	6	12	10
E	0.77	1	16	7
F	0.29	2	19	11
G	0.19	1	14	6
H	0.17	4	21	6
I	0.05	4	21	11
J	0.03	4	19	19
K	0.01	2	20	14

Figure 4 shows, for each scenario, the total of the cost of the PSS field repair kit. The results show that in order to meet the PSS availability requirement of 95%, the total cost of the field repair kit must increase by more than 60% over that of the originally proposed field repair kit composition in Scenario 1. However, when the PSS availability requirement constraint is relaxed to 90%, the cost of the field repair kit was significantly reduced, nearly down to 50% of the field repair kit cost shown in Scenario 2. In other words, increasing the availability requirement by 5% resulted in a 50% increase in the total cost of the field repair kit. Additionally, it is observed that if 90% PSS availability is acceptable to the customer, the optimized field repair kit can be composed for lesser cost than the original field repair kit proposed by the design team.

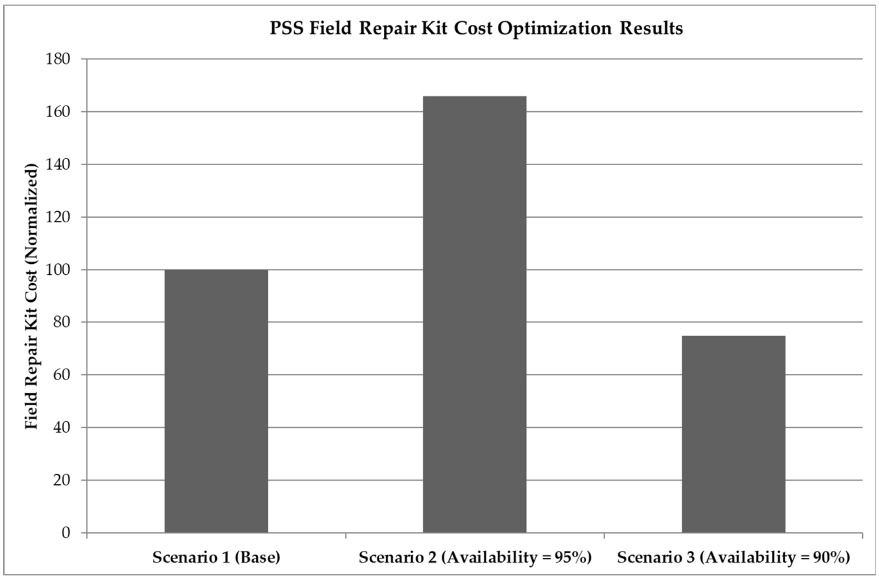

Figure 4. Field repair kit cost optimization results for scenarios analyzed.

As in the last step, using the optimized field repair kit composition, Monte Carlo simulation was performed to estimate the confidence level for which the PSS can meet the availability requirement for each scenario. Two parameters were used. The first parameter was the failure rate of each spare part. Distribution of spare parts failure rates were set based on the historical reliability data of the part or similar parts. The second parameter was the PSS usage. Since PSSs are used by many customers, but with different monthly usage, the PSS monthly usage was set with triangular distribution with a minimum value of 5.7 million uses and a maximum value of 10.2 million uses, with a mean usage of 8.0 million per month. This was based on the estimate from the design team. The resulting distribution of availability requirement was analyzed to determine the confidence level for the optimized field repair kit to meet the target PSS availability. The confidence level of availability that the PSS can achieve with the optimized field repair kit is plotted in Figure 5. For each scenario, 10,000 simulation runs were performed with the spare parts failure rate distribution and the periodic PSS usage distribution. The horizontal axis represents the confidence level, while the vertical axis represents the PSS availability.

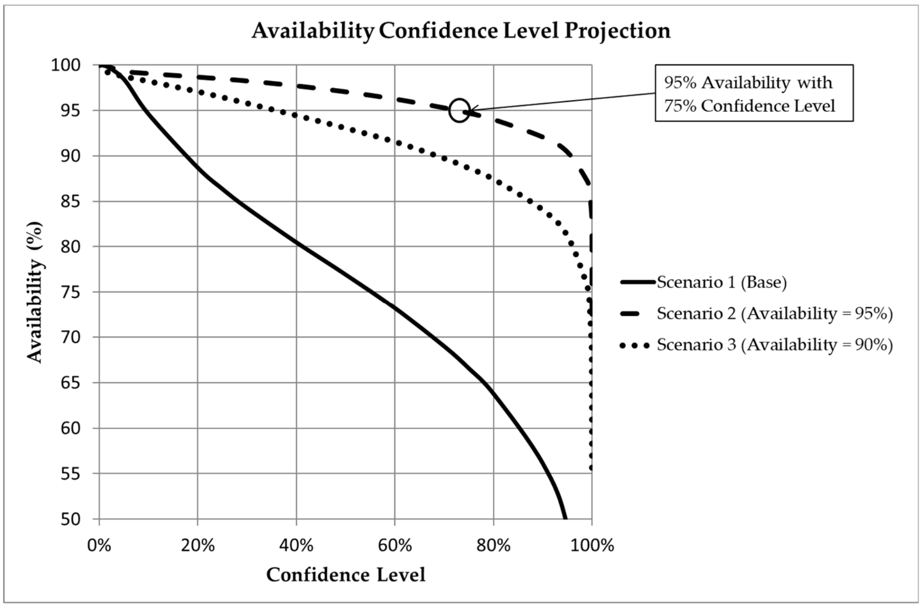

Figure 5. Availability confidence level of the PSS with optimized field kit in place.

In the figure, the topmost curve shows the confidence level of the PSS with the field repair kit optimized for 95% availability. The specific data point singled out shows that this particular PSS with the optimized field repair kit can meet the 95% availability requirement with a 75% confidence level. The second curve shows the confidence level of the PSS with field repair kit optimized for 90% availability. It shows a 70% confidence level for meeting the 90% availability target. Finally, the two optimized field repair kits, in contrast with the original field repair kit in the base scenario, performed particularly well in terms of expected confidence level to meet the PSS availability requirements. Results obtained and shown in Figures 4 and 5 and Table 5 can be a valuable guideline for assessing the PSS availability with a specific field repair kit. Cost savings realized by the adjustment of the field repair kit inventory should be balanced against the expected PSS confidence level for meeting availability requirement promised to customers. The company can also create a mitigation plan based on the confidence level to minimize the risk of not meeting the availability requirement.

4. Conclusions

In this paper, an industrial PSS field repair kit optimization case study of was presented. The objective of the case study was to cost optimize the composition of a field repair kit placed at a customer's site, while maintaining a specific level of PSS availability. A high fidelity PSS simulation model was created and utilized to construct the PSS availability regression model. The availability model was used with other spare parts information to cost optimize the field repair kit, subject to the PSS availability requirements. Monte Carlo simulation was performed to assess the confidence level at which the optimized PSS field repair kit can meet the availability requirements.

Results showed that the PSS field repair kit can be cost optimized to satisfy the availability requirements imposed by the contract with the customer. It was also revealed that the marginal cost of availability improvement was very high, resulting in an almost twofold increase in cost to improve the availability by 5%. The investigation of the optimized PSS repair kit composition showed that the PSS should never shut down for a low cost spare part, but should only shut down for a very expensive spare part that is too expensive to be included in the field repair kit. Finally, Monte Carlo simulation results showed that the optimized PSS field repair kit performed better than the originally proposed field repair kit, meeting the availability requirements at a higher level of confidence. The overall case study results were encouraging in that the modeling and optimization process shown in this paper is applicable to other complex systems.

Future works regarding the improvement of PSS can expand into multiple directions. The latest advances in big data, information and communications technology (ICT), and internet of things (IoT) can greatly improve preventive and predictive maintenance practice for PSS. This can be accomplished through better prediction of parts failure interval and failure modes through analysis of historical data and real-time feedback from the PSS. Big data and IoT can be utilized to design the improved spare parts supply chain as well, providing information for an appropriate inventory level, stocking locations, and reorder points based on PSS location and usage. Another direction the research can take is the improvement of the PSS design: how can PSS be architected for optimum preventive or predictive maintenance policy? How does the PSS architecture impacts spare parts logistics or its supply chain structure? In addition to the topics mentioned, another fundamental direction that the PSS related research can take is to explore ways to reduce the limitation imposed for implementing PSS, such as willingness to adopt the PSS by companies, willingness to accept the PSS by customers, and dealing with environmental implications. All these are very promising future research topics to explore.

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