Chapter 19
Product-Service Systems Under Availability-Based Contracts: Maintenance Optimization and Concurrent System and Contract Design

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Abstract Product-service systems (PSSs) are the result of a shifting business focus from designing and selling physical products, to selling a system consisting of products and services in an ongoing relationship with the customer that fulfills customer satisfaction. A PSS contract can take several forms (e.g., fixed price, capability-contract, and availability-based). The focus of this chapter is on PSSs that use availability-based contracts. In these cases the customer does not purchase the product, instead they purchase the utility of the product and the availability of service in order to obtain a lower cost while still meeting their needs. This chapter addresses the optimization of system maintenance activities, and the concurrent design of the PSS and the contract.

19.1 Introduction

Performance-based contracts (PBCs) and similar mechanisms have become popular for contracting the sustainment of military systems in the United States and Europe. Performance-based logistics (PBL), also referred to as performance-based life-cycle product support and contracting for availability, refers to a group of strategies for system support that instead of contracting for goods and services, a contractor delivers performance outcomes as defined by performance metric(s) for a system or product [1]. Performance-based thinking is reflected in a famous quote from Levitt

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[2]: “The customer doesn’t want a drilling machine; he wants a hole-in-the-wall.” PBL and similar outcome-based contracts pay for effectiveness (availability, readiness and/or other performance measures) at a fixed rate, penalize performance shortcomings, and/or award gains beyond target goals.

The impact of a performance-based contract oriented design process on original equipment manufacturer (OEM) decision making for optimizing reliability in the post-production purchase period led to the development of integrated schemes with dynamic interdependencies of the product and the service the product provides called product-service systems (PSSs) [3].[1] One example of a PSS is the function of washing clothes using a washing service. In this case, customers pay for the laundering of their clothes instead of buying the washing machine. This example, called pay-per-wash, is described in [4]. When providing a function instead of a product, a contract must be entered into between the customer and the service provider (the contractor). Here, the connection between the stakeholders becomes formal, and the contracts that regulate what the offer includes are important [5].

Procurement and system acquisition process efficiency and success across a system’s life cycle requires the development and implementation of best-value, long-term, performance-based product support strategies that leverage performance-based agreements with both industry and government product support providers [6]. Hence, an effective combination of technical and monetary approaches that includes the inventory, maintenance, and operational decisions together to form a unified model that provides visibility into the effect of different decisions is required [7]. Performance-based logistics (PBL) contracting is intended to incentivize this integration towards concurrently reducing life-cycle cost and improving performance.

Availability-based contracts that pay for maintenance or service effectiveness and penalize shortcomings in the specific availability metric (e.g., materiel, operational, or inventory-level availability) have been introduced to incentivize cost reduction efforts and guarantee readiness on the contractor side of PSS. These types of contracts are also referred to as “performance-based” contracts (PBC), “outcome-based contracting maintenance models,” “performance-based logistics” (PBL) and “contracting for availability” (CfA). Availability-based contracting concepts are being used for PSS acquisitions in healthcare, energy, military systems and infrastructure. These contracts allow customers to pay only for the specific outcomes (e.g., availability) achieved rather than the workmanship and materials being delivered.

Every PSS has two sides: the customer who expects a specific level of outcome (e.g., availability) over the period of the contract, and the contractor who provides the outcome for the period of the contract and its possible extension.

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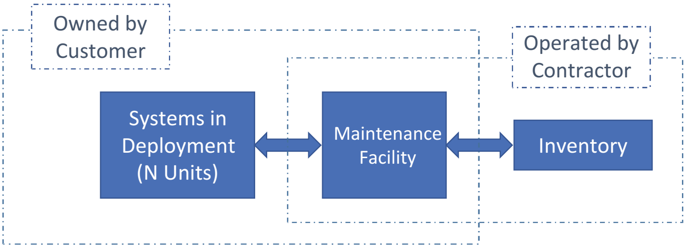
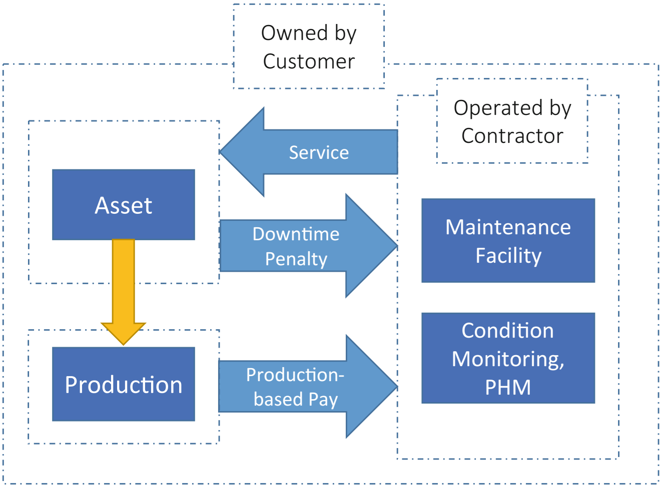
[1] We assume that ideally the design of the PSS means designing the hardware, software, service, and logistics associated with the system concurrently. Section 19.4 of this chapter includes contract design in this process as well.



(a) Non-revenue earning for the customer



(b) Revenue earning for the customer

Fig. 19.1 Repairable item flow under an outcome-based contract describing possible customer/contractor relationships

There are several possible ways to share the tasks, risks and measure the outcome in these contracts. Figure 19.1 illustrates two possible contractor/customer relationships. For example, Fig. 19.1a shows a case where the contractor operates a repair facility that is owned by the customer and is in charge of replacement and repair of the systems. In this case, the contractor is only committed to maintain the inventory availability (e.g., [8]) or is in charge of the availability of the deployed systems using fleet-level availability metrics [9].[2] The contractor incurs the costs associated with shipping, holding and ordering, and receives a payment from the customer. The customer generally does not produce any income from the operation

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[2] Classically "inventory" refers to an inventory of items (e.g., spare parts), however, more generally, it could mean a maintenance "opportunity inventory", which is a combination of all the resources necessary to support the system, i.e., workforce, facilities, favorable weather, and spare parts. This broader interpretation of inventory (previously eluded to by [10]) is a departure from mainstream operations research that only thinks of inventory as parts.

and one can call this process non-revenue earning from the customer's perspective. The optimization of logistics, maintenance and the system's design will be done by the contractor without the customer's involvement.

Another possible contractor/customer relationship that is common for systems that are revenue-earning for the customer is shown in Fig. 19.1b. In this case the relationship is based on two-levels of production payment and downtime penalty based on opportunity cost. The customer makes revenue from production and pays the contractor based on the combination of its revenue as well as penalizing for operational downtime. In this perspective the availability of production is the critical attribute for the customer, but the measure of production is also dependent on other production factors (e.g., in a wind farm it depends on wind speed). From the contractor point of view there is a payment or penalty for every hour of operation.

Revenue-earning and non-revenue-earning are customer distinctions, from the contractor's viewpoint, everything is revenue earning (if it wasn't there would be no contract). Systems can also be distinguished based on the form of the outcome. For production systems the contractor's compensation is determined by a payment schedule that is based on the amount or quantity of outcome the system produces. For non-production systems, the contractor's compensation is determined by a payment schedule that is based on the availability of the system.

One of the merits of availability-based contracts is the optimal sharing of risks by both parties. However, this presents several challenges. First, the optimization of system sustainment differs depending on whether: (a) the system is managed in isolation, or (b) the system is part of a larger population of systems managed by an availability-based contract. Secondly, availability-based contracts present a pricing challenge due to the stochastic nature of system's performance, customer usage, the outcomes of the contractor's decisions, and the impact of these contracts on the risk-sharing balance. Failures to understand the PSS's sustainment impacts and the risks involved, and therefore the contract cost, have caused some projects to stop and given rise to doubts about the applicability of this class of strategies for new acquisition contracts.

This chapter has two parts. First we discuss the incorporation of availability-based contract requirements into the optimal design of the maintenance of systems (Sect. 19.3), and second, progress toward concurrent PSS design and contract design (Sect. 19.4). However, before discussing the maintenance optimization and concurrent design aspects, it is useful to briefly review general contract modeling.

19.2 Contract Modeling

Contracts can be modeled from several different viewpoints, however, it is most useful to model the class of contracts discussed in this chapter from the contractor's point of view as a payment model that addresses the desired outcome constraints in which performance and cost are weighted into a single factor to simplify the payment rationale [9],

$$P_t(C_t, A_t) = \omega_t + \alpha_t C_t + v_t A_t \tag{19.1}$$

where P_t is the payment to the contractor, C_t is the cost to the contractor, A_t is the availability, and $\omega_{t,}$ α_t and v_t are the contract parameters chosen by the customer and described in the contractual document where t refers to the monitoring interval. Note, for simplicity, Eq. (19.1) ignores the contractor's profit. ω_t is the fixed payment. α_t is the customers' share of the contractor's costs of operation and v_t is the penalty or award rate for achieved availability below or above the required level.

By varying the contract parameters in Eq. (19.1), different classes of cost-driven and outcome-based contracts can be modeled. For example, $v_t = 0$ and $\alpha_t = 0$ is a fixed-price contract, and $v_t = 0$ and $\alpha_t = 1$ is a cost-plus contract with full reimbursement. Since this model is completely known to the contractor it is safe to assume that they optimize their decisions based on the above model. However, their decisions might incur costs on the customer outside of the scope of the contract, for example maintenance costs after the contract is over (i.e., so called silent hazards).

From the viewpoint of customer these contracts can be modeled by a Stackleberg game in which, depending on the contract designed by the customer, the contractor will optimize its strategy. From this point of view a modeling can be done by a two-level optimization problem [11].

In this chapter we consider two different ways of modeling contracts. In Sect. 19.3 we use a payment model to directly model the contractor and we ignore the interaction between the contractor and the customer except when considering discrete maintenance opportunities. In Sect. 19.4.2 we describe a two-level stochastic optimization schemed used to optimize the contract and the maintenance actions.

19.3 Optimization of Maintenance Activities in PSSs Under Availability-Based Contracts

This section presents the concept of PHM-enabled maintenance options. Then, it describes how the requirements from an availability-based contract are incorporated into an option valuation process in order to optimize the maintenance planning for systems.

19.3.1 System Health Management as a Maintenance Design Activity

The maintenance planning that this chapter focuses on is contingent on the presence and use of system health management technologies. System health management technologies such as condition-based maintenance (CBM) seek to perform predictive maintenance based on the condition of the system. Prognostics and health management (PHM) uses the condition of the system coupled with the expected future environmental conditions (temperature, vibration, etc.) to forecast a remaining useful life (RUL). The system management challenge is how to perform an accurate system risk allocation using the predicted RULs (with their associated uncertainties) to optimally plan when to perform predictive maintenance and allocate maintenance resources. The optimal maintenance planning is modified by performance requirements imposed by the availability-based contracts.

19.3.2 Maintenance Planning Using Real-Option Analysis

This section presents the concept of PHM-enabled predictive maintenance options. In Sect. 19.3.3 we describe how the requirements from an outcome-based contract are incorporated into the option valuation process.

A real option is the right, but not the obligation, to undertake certain business initiatives, such as deferring, abandoning, expanding, staging, or contracting. For example, the opportunity to invest in an asset is a real "call" option. Real options differ from financial options in that they are not typically traded as securities, and do not usually involve decisions on an underlying asset that is traded as a financial security. Unlike conventional net present value analysis (discounted cash flow analysis) and decision tree analysis, real options model the flexibility management has to alter the course of action in a real asset decision, depending on future developments. Predictive maintenance options are created when in situ health management (i.e., PHM) is added to systems. In this case the health management approach generates a remaining useful life (RUL) estimate that can be used to take proactive actions prior to the failure of a system. The maintenance option when PHM is used is defined by Haddad et al. [12],

- Buying the option = paying to add PHM to the system
- Exercising the option = performing predictive maintenance prior to system failure after an RUL indication
- Exercise price = predictive maintenance cost
- Letting the option expire = doing nothing and running the system to failure then performing corrective maintenance

The value from exercising the option is the sum of the cumulative revenue loss and the avoided corrective maintenance cost (corrective maintenance being more expensive than predictive maintenance).

The cumulative revenue loss is what the system would earn between the predictive maintenance event and the end of the RUL (if no predictive maintenance was done). Restated, this is the portion of the system's RUL that is thrown away when predictive maintenance is done prior to the end of the RUL. In reality, this cumulative revenue takes the form of loss in spare part inventory life (i.e., the revenue earning time for the system will be shorter because some inventory life has been disposed of) [13].

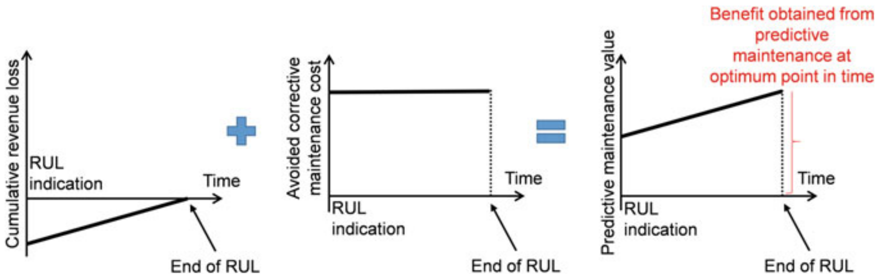

Fig. 19.2 Predictive maintenance value construction [13]

Avoided corrective maintenance cost includes[3]: the avoided corrective maintenance parts, service and labor cost, the avoided revenue loss associated with corrective maintenance downtime and the avoided under-delivery penalty due to corrective maintenance (if any).

Figure 19.2 illustrates the construction of the predictive maintenance value. The cumulative revenue[4] loss is the largest on day 0 (the day the RUL is forecasted). This is because the most remaining life in the system is disposed of if predictive maintenance is performed the day that the RUL is predicted. As time advances, less RUL is thrown away (and less revenue is lost). The avoided corrective maintenance cost is assumed to be constant. The predictive maintenance value is the summation of the cumulative revenue loss and the avoided corrective maintenance cost (Fig. 19.2). If there were no uncertainties, the optimum point in time to perform maintenance would be at the peak value point (at the RUL), which is the last moment before the system fails. Unfortunately, everything is uncertain.

The primary uncertainty is in the RUL prediction. The RUL is uncertain due to inexact prediction capabilities, and uncertainties in the environmental stresses that drive the rate at which the RUL is used up. A “path” represents one possible way that the future could occur starting at the RUL indication (Day 0). The cumulative revenue loss paths have variations due to uncertainties in the system’s availability or uncertainties in how compensation is received for the system’s outcome.[5] The avoided corrective maintenance cost paths represent how the RUL is used up and vary due to uncertainties in the predicted RUL. Each path is a single member of a population of paths representing a set of possible ways the future of the system could play out.

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[3] This is not the difference between the predictive and corrective maintenance actions, but rather the cost of just a corrective maintenance event. The predictive maintenance event cost is subtracted later when the real option value is determined, i.e., in Eq. (19.2).

[4] The value construction in this section assumes that the system is revenue earning, e.g., a wind turbine or an airplane used by an airline.

[5] For example, if the system is a wind turbine, path uncertainties could be due to variations in the wind over time.

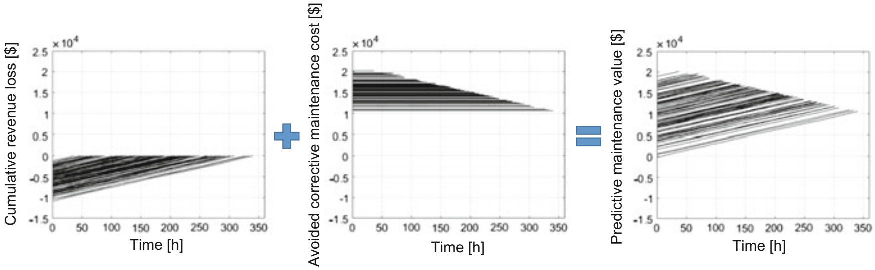

Fig. 19.3 Example of the simulated paths after an RUL indication

Due to the uncertainties described above, there are many paths that the system can follow after an RUL indication as shown in Fig. 19.3. Real options analysis lets us evaluate the set of possible paths to determine the optimum action to take.

Consider the case where predictive maintenance can only be performed on specific dates.[6] On each possible maintenance date, the decision-maker has the flexibility to determine whether to implement the predictive maintenance (exercise the option) or not (let the system run to failure, i.e., let the option expire)[7]. This makes the option a sequence of "European" options that can only be exercised at specific points in time in the future. The left side of Fig. 19.4 shows two example predictive maintenance paths (diagonal lines) and the predictive maintenance cost (the cost of performing the predictive maintenance). Real Option Analysis (ROA) is performed to valuate the option where the predictive maintenance option value is given by

$$O_{PM} = Max(V_{PM} - C_{PM}, 0) \tag{19.2}$$

where V_{PM} is the value of the path (right most graph in Fig. 19.3 and the diagonal lines in Fig. 19.4), and C_{PM} is the predictive maintenance cost. The values of O_{PM} calculated for the two example paths shown on the left side of Fig. 19.4 are shown on the right side of Fig. 19.4. Note that there are only values of O_{PM} plotted at the maintenance opportunities (not between the maintenance opportunities).

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[6] This could be due to the limited availability of maintenance resources or the limited availability of the system being maintained.

[7] The decision-maker may also have the flexibility not to implement the predictive maintenance on a particular date but to wait until the next possible date to decide, which makes the problem an American option style as has been demonstrated and solved by [12]. The Haddad et al. solution in [12] is correct for the assumption that an optimal decision will be made on or before some maximum waiting duration and the solution delivered is the maximum "wait to date". Unfortunately, in reality maintenance decision-makers for critical systems face a somewhat different problem: given that the maintenance opportunity calendar is known when the RUL indication is obtained, on what date should the predictive maintenance be done to get the maximum option value. This makes the problem a European option style.

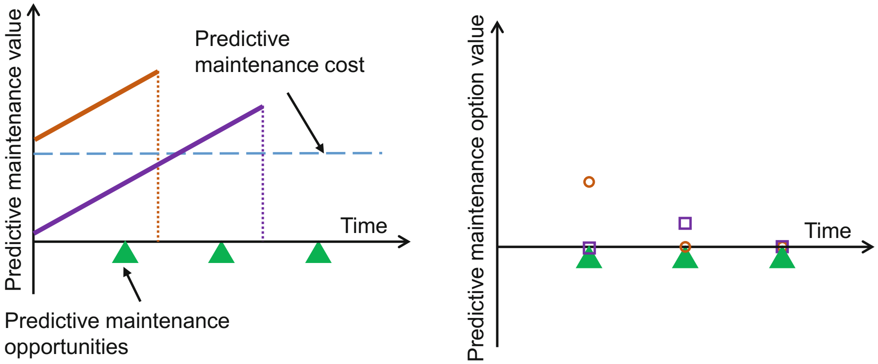


Fig. 19.4 Real options analysis (ROA) valuation approach. *Right graph*: *circles* correspond to the upper path and the *squares* correspond to the lower path in the *left graph*. The *triangles* indicate predictive maintenance opportunities

Equation (19.2) only produces a non-zero value if the path is above the predictive maintenance cost, i.e., the path is "in the money".

Each separate maintenance opportunity date is treated as a European option. The results at each separate maintenance opportunity are averaged to get the expected predictive maintenance option value of a European option expiring on that date. This process is repeated for all maintenance opportunity dates. The optimum predictive maintenance date is determined as the one with the maximum expected option value. The detailed mathematical formulation of the solution can be found in [13].

19.3.3 Incorporating Availability-Based Contract Requirements into the Predictive Maintenance Option

The "paths" described in Figs. 19.2 and 19.3 are based on a production system with an "as-delivered" energy delivery contract for a wind farm that defines a single fixed price for each unit of the energy delivered. When a system is managed via an availability-based contract (like a PBL), the paths shown in Fig. 19.3 will be impacted. The availability-based contract influences the combined predictive maintenance value paths due to changes in the cumulative revenue loss and the avoided corrective maintenance cost paths. These paths will be influenced by the availability target, prices before and after that target is reached (generally the latter is lower than the former), penalization mechanisms, the availability already produced, and the operational state of the other systems in the population. For example, assume that the cumulative availability produced by a population of systems is close to the availability target. All systems are operational while some are indicating

RULs. The population of system can meet the availability target without the members indicating RULs. Then the cumulative revenue loss of the systems with RULs will be lower than when they are managed under a non-availability-based contract, since the cumulative revenue loss will be lower (because the price paid for the availability is lower after the outcome target is met). Assume a different scenario where the cumulative outcome from the population of systems is far from the outcome target, and many systems are non-operational. In this case, running the systems with RULs to failure and performing corrective maintenance causing long downtimes may result in the population of the systems not reaching the outcome target. In this case the under-delivery penalty will occur, and the avoided corrective maintenance cost will be higher than the non-availability-based contract (as delivered) case that doesn't have any penalization mechanisms.

Under an availability-based contract, the optimum predictive maintenance opportunity for individual systems in a population (e.g., a fleet) are generally different than for an individual system managed in isolation. These two cases would have the same optimum if an as-delivered contract was used.

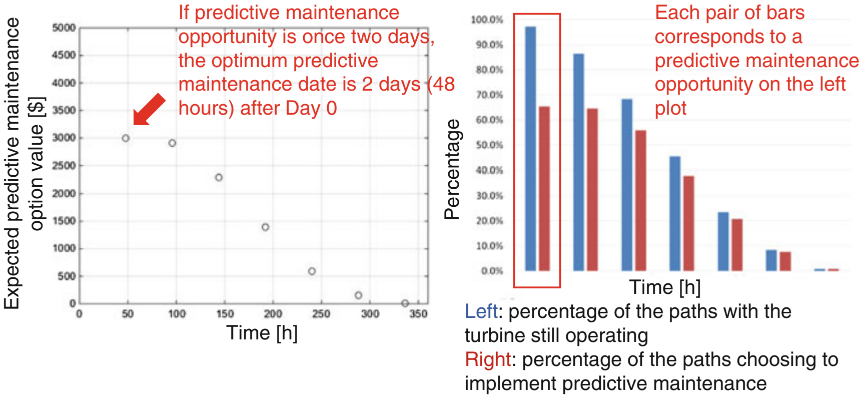
19.3.4 A Wind Turbine with an Availability-Based Contract

In this Section, the predictive maintenance option model is implemented on a single turbine and then a wind farm with multiple turbines is managed via an availability-based contract. A Vestas V-112 3.0 MW offshore wind turbine [14] was used in this example.

Maintaining offshore wind turbines requires resources that are not continuously available. These resources include ships with cranes, helicopters, and trained maintenance personnel. These resources are often onshore-based (which may be as much as 100 miles from the wind farm) and may be maintaining more than one wind farm. Therefore, maintenance is only available on scheduled dates (maintenance opportunities) that may be weeks apart. The availability of maintenance is also dependent on weather and ocean conditions making the timing of future maintenance visits uncertain.

Figure 19.5 shows an example result for a single wind turbine. In this example, the ROA approach is not trying to avoid corrective maintenance, but rather to maximize the predictive maintenance option value. In this example, at the determined optimum maintenance date the predictive maintenance will be implemented on only 65.3% of the paths (the paths that are "in the money"). 32.0% of the paths, which are "out of money", will choose not to implement predictive maintenance, and in 2.7% of the paths the turbine has already failed prior to that date.

The result in Fig. 19.5 assumes that all the power generated by the turbine can be sold at a fixed price. There are many wind farms (and other renewable energy power production facilities) that are managed under availability-based contracts called power purchase agreements (PPAs). A PPA defines the energy delivery targets, purchasing prices, output guarantees, etc. Wind farms are typically



If predictive maintenance opportunity is once two days, the optimum predictive maintenance date is 2 days (48 hours) after Day 0

Each pair of bars corresponds to a predictive maintenance opportunity on the left plot

Left: percentage of the paths with the turbine still operating

Right: percentage of the paths choosing to implement predictive maintenance

Fig. 19.5 Optimum maintenance date after an RUL indication for a single wind turbine

managed via PPAs for several reasons [15]. First, though wind power can be sold into the spot market, the average spot market prices vary greatly (above and below) the long-term PPA contract prices. Second, lenders are not willing to finance wind projects without a signed PPA that secures a future revenue stream. Third, wind energy buyers prefer simply purchasing power to building and operating their own wind farms.

PPA terms are typically 20 years for wind energy, with either a constant or escalating contract price defined through the whole term. At the beginning of each year, a PPA often requires the seller to estimate how much energy they expect to generate during the whole year, based on which an annual energy delivery target. For energy that is beyond the annual energy delivery target a lower excess price may apply. The buyer may also have the right not to accept the excess amount of energy, or adjust the annual target of the next contract year downward based on how much has been over-delivered. A minimum annual energy delivery limit or output guarantee may also be set, together with a mechanism to determine the liquidated damages. For example, the seller must compensate the buyer for the output shortfall that the buyer is contracted to receive, multiplied by the difference between the replacement energy price, the price of the energy from sources other than wind paid by the buyers to fulfill their demands, and the contract price. The buyer may also adjust the annual target of the next contract year upward to compensate for how much has been under-delivered.

Assume a 5-turbine-farm managed via a PPA, Turbines 1 and 2 indicate RULs on Day 0, turbine 3 operates normally, and turbines 4 and 5 are non-operational. Predictive maintenance value paths of all turbines with RULs need to be combined together because maintenance will be performed on multiple turbines on each visit (see [16] for details on how the paths are combined for multiple turbines). Cumulative revenue loss, avoided corrective maintenance cost, and predictive maintenance value paths for turbines 1 and 2 are shown in Fig. 19.6.

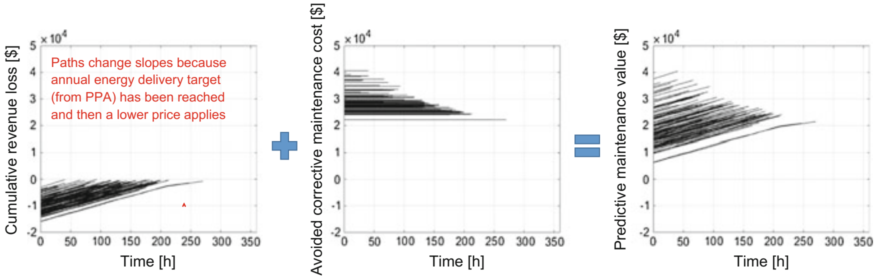


Fig. 19.6 Combined value paths for turbines 1 and 2 in a 5 turbine farm managed by a PPA. Some paths (as indicated by the *arrow*) change slopes because the annual energy delivery target defined by the PPA has been reached after which a lower price for the power applies

19.4 Concurrent PSS and Contract Design

In Sect. 19.3, the PPA (the contract) sets the requirements for the system, and the maintenance planning is optimized based on those requirements. This is a case where the availability-based contract design has been performed separately from the through-life engineering services (TES) and engineering design processes, and provided as a requirement to the engineering design process. This approach may create significant risks for both parties. For systems that are subject to availability-based contracts, contract failure may mean large amounts of money spent by the customer (potentially the public) for either no availability or inadequate availability, or result in the contractor being driven out of business, which can lead to disaster for both parties.

A fundamental gap exists between contract design and engineering (PSS) design. This section discusses the current state of contract/PSS design and progress toward concurrent system and contract design.

19.4.1 State-of-the-Art in Contract-Based System Design

Traditionally, the contract and product parameters are defined separately. In recent years, driven by a need for enhancing system reliability, maintainability, and logistics support, attempts to include contract and engineering (performance) parameters simultaneously have been articulated, but has not been done. There are a significant number of papers with a wide array of measures to determine performance, taking both objective and subjective views.

In this section, the relevant approaches for designing contracts and products are reviewed and the need for concurrent contract-engineering design is introduced as a key solution to obtain a more realistic overall PSS design.

The correlation between contracts and the PSS design process can be classified into three categories:

(1) Engineering/logistics design using fixed contract parameters

In this category, it is assumed that the contract parameters are given as a set of requirements, and they are treated as fixed input parameters in the PSS design (i.e., they are constraints on the PSS design). Hence, the PSS parameters are designed to maximize the operating performance and functionality that satisfies the contract requirements.

Examples of product design processes (hardware and/or software) that include one or more contract parameters, e.g., cost constraints, length of support requirements, etc., are very common. The analysis in Sect. 19.3 is an example of this category of work where PPA requirements (energy price and the annual delivery target are used to perform maintenance planning design for the wind farm). Other examples include Nowicki et al. [17] who developed a spare provisioning system to respond to a given performance-based contract from the viewpoint of the contractor. In [17] the contractor's objective is to maximize profit and the scope of its activity by optimizing the inventory level (the inventory level is considered to be part of the logistics design). This scheme also includes sensitivity analysis that addresses the reliability of the product.

Less common are PSS design processes that use actual availability requirements. Jazouli et al. [18, 19] estimated the required logistics, design, and operation parameters for a specific availability requirement. In this work the developed model connects the requirements on each operational decision regarding repair, replacement and inventory lead-time so that the impact of the contract terms can be seen on the logistics decisions. Jin and Wang [20] studied the impact of reliability and usage uncertainty on planning PBCs incorporating equipment availability, mean-time-to-failure, and mean-time-to-repair.

(2) Contract design that uses fixed product parameters

In this category, the contract parameters are optimized for a given PSS. For example, the following contract parameters may be determined: the payment schedules (amount and timing) [21], profit sharing [22], the length of contract [23], the selected contract mechanism [17, 24], supply-chain parameters (inventory lead time,[8] back-order penalties, etc.) [25], and warranty[9] design could be determined.

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[8] In [18] the inventory lead time (ILT) was considered to be a logistics parameter determined from an availability requirement. It is also possible that ILT is a contract parameter that is flowed down to subcontractors.

[9] Although we include warranty design in the list of possible contract design activities that could be driven by the product parameters, for most products that have warranties, the type of warranty and its length are determined by marketing, and are not based on the product's predicted reliability. More commonly, the warranty type and length (which are a contract) are passed to the engineering design to determine the appropriate warranty reserve fund, which would be an example of the first category.

Examples of work in this category include Arora et al. [26] who studied an integrated inventory and logistics model to minimize the total cost of supply-chain support. Nowicki et al. [17] developed a model that designs performance-based contracts with different lengths and contract fees. In this work the contract design is based on a given product with a fixed initial reliability. They explore the opportunity for further investment in improvements in the product's reliability under the proposed PBC to demonstrate a win-win for the customer and contractor through the optimal choice of contact length.

Hong et al. [24] employed mechanism design theory[10] to design an optimized maintenance service contract for gas turbines in which uncertainties associated with customer actions, engine performance, and maintenance costs during the contract execution phase were accounted for. They assumed that the gas turbine design was given and determined the contract that maximizes the expected profit and provides a win-win incentive for the customer and contractor.

Wang [27] developed and discussed three different contract options for maintenance service contracts between a customer and a contractor for a given system design. The contract options were: (1) a full contract that covers both inspections and inspection repairs, and failure repairs, (2) a partial contract that covers inspections and inspection repairs, but not the failure repairs, and (3) a partial contract that covers failure repairs only.

In this category, there are several challenges. The existing models require a better understanding of the impact of incentive structures on the system design and usage. Zhu and Fung [25] proposed a model based on the service delivery and customer satisfaction level. They studied the design of optimal contracts that balance the incentives and risks on the two sides of a contract, so that both can achieve maximum profits. They assume that incentive payments to the contractor are dependent on the contractor's performance. Further research is also required on the risk attitude of contractors: risk-aggressive, risk-averse, or prudent. In addition, a more general and comprehensive model would include flexibility for the service provider to change their level of effort during the project to increase the chances of meeting their contractual goals. Moreover, an important gap in contract theory models is the assumption of a static risk allocation for the entire length of a project.[11] Zhao and Yin [28] propose a theoretical model for a dynamic risk allocation in constructing a project. However, a successful dynamic risk allocation needs a comprehensive understanding of both engineering and contractual parameters and their variations throughout a project. Such a dynamic risk allocation is not addressed in any theoretical models and is the subject of the next category.

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[10] Mechanism design theory is an economic theory that seeks to determine when a particular strategy or contract mechanism will work efficiently.

[11] This problem is also evidenced by the choice of a single value for the cost of money, i.e., the cost of money is not constant over time (nor the same for all projects within an organization).

(3) Concurrent design of the contract and the PSS

Finally, the concurrent design of both the contract and the PSS would be the ideal solution (for both the customer and contractor) for real applications. However, there are no models that accurately assess and design CfA, dealing with all the risks and uncertainties involved [29]. One important proposed solution to fill this gap is to use engineering inputs and to find the engineering connections to current theoretical contract models [30]. Kashani Pour et al. [31] reviewed existing analytical models in this space and developed a framework for the design of availability-based contracts with consideration of engineering design and incentive structure.

There is an increasing interest in employing PBC concepts to obtain a better mutual understanding between the supplier and the customer. However, the existing literature is primarily focused on solving the problem from the contractor point of view and does not address the role of optimum contract design from the customer's viewpoint. This is partially due to the relatively short history of this class of contract [29], a lack of sufficient public data on different design contracts, and ignorance of the dynamic impact of uncertainties in the existing models.

A few authors discuss the need for concurrent design, e.g., [17]; even fewer attempt to provide any type of solution to the problem [24], and in cases that claim to address both the customer and contractor, the solutions are primarily sensitivity analyses that ignore the asymmetry of information or moral hazard problem.[12] Another proposed approach (also sensitivity analysis) is to study the impact of engineering parameters on the construction of contracts [32]. Sols et al. [32] studied the formulation of an n-dimensional performance-based reward model for use in PBC contracts. They developed an n-dimensional metrics structure that represents the system effectiveness along with its reward model that results in a successful PBC contract.

The type of cost modeling necessary for concurrent engineering and contract design isn't the same as for either engineering or contract design alone [5]. Most of the current CfA decisions are based on expert opinions, estimation, and historical data from previous designs, which can be unreliable [33]. In addition, such an approach is less useful when system complexity increases [34]. Also, a lack of relevant historical data is a major source of challenge in new projects [33, 34].

Based on Kashani Pour et al. [31], solutions provided in this category should be able to address the requirements breakdown (or flow down) to subcontractors. The breakdown of requirements for use by sub-system designers shares the freedom provided by availability-based contracts. Solutions are also required to provide concise algorithms so that the availability will be tangible

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[12] While there are some major manufacturers who appear to (or claim to) use an integrated approach in concurrently designing contract and product parameters, they are unpublished and no details are available.

and measureable, and so the contractor can implement and understand the requirements within their sustainment activities. Designing availability-based contracts should address reliability design of products and operational decisions based on condition monitoring technologies, the role of incentives and their impact on the life-cycle of the product, supply-chain management of the PSS, and the integrated design and joint optimization of different performance metrics. These requirements make the use of concurrent design of PSS and contracts a necessary approach to model the problem for application to real-world practice.

The key questions that should be answered in this category are: (1) What are the main elements of an availability-based contract for a PSS? (2) What are the essential attributes of the concurrent PSS and contract design process? And (3) How are the advantages of concurrent design of PSS and contracts versus the first two category of design verified?

To summarize the concurrent design of the contract and PSS needs to address both the contractor and customer and the dynamics created by the contractual term between them including addressing uncertainties in achieving availability or reliability-related challenges. Concurrent design considers contract design as a part of integrated system design with PSS and the contract of main sub-systems with a dynamic relationship that is subject to stochastic processes such as reliability, supply-chain demand and operational uncertainties.

19.4.2 Contract Design as a System Design Problem

We approach contract design concurrent with the PSS as a system design problem where the process of designing contractual terms that address performance metrics, the payment model, and performance assessment are design parameters and a multidisciplinary life-cycle simulation of design impacts needs to be integrated into the engineering design process. The significant challenge of contract design in practice is on the customer side.

In the case of availability-based contracts, the TES and engineering designs should determine the contract requirements and the contract length and price in the acquisition and procurement stage, so that it protects the interests of the customer throughout the life cycle (i.e., it does not overpay the contractor, but also minimizes the risk that the system will become unsupported).

19.4.2.1 A Concurrent Contract and System Design Example

The study summarized in this section is the availability-based contract for spare-part availability for a submarine fleet (in this case the spare part is a torpedo). Each item in the inventory is a spare subassembly for a fleet of end-products that are carrying out a specific mission. Exercises and deployment requires continuous service of torpedoes before being returned to the fleet for usage. When the torpedoes are being tested, if they are found to be defective, they are replaced from inventory by supply contractors. The data and details of this example can be found in [7]. In this case the relationship between contractor and customer is similar to Fig. 19.1a.

The objective of the contract design process is to determine the best penalty and reward rate along with the best assessment interval (the interval over which to measure availability) as a contract parameter to reduce the total cost of the system and guarantee availability requirements. This optimum assessment interval should also be robust with respect to uncertainties in the costs that the contractor will incur. Since the cost model of the contractor is determined by penalty function parameters such as back-order and holding cost, and these costs are not related to the customer, a careful study of these contractual parameters needs to be done by the customer.

Back-order cost is primarily driven by opportunity cost, the cost of down-time or in general unavailability cost. It can be given a fixed pre-determined value or be connected to a variable source similar to production-guarantee contracts. Knowing all these helps the customer to decide on the cost of a back-order.

The contractor's cost of holding an inventory comes from the actual cost of operating the inventory facility and the penalties that are incurred because the inventory level is kept low. In this case the inventory facility is owned by the customer and the customer defines the holding costs that the contractor pays; in general the customer prefers a higher reliability and a lower level of inventory. The penalty is assigned to a actual holding cost (h_a) by adding a penalty rate h_p where the overall holding cost is given by $h = h_a + h_p$. Similarly the back-order is closely related to availability. The back-order cost (from the customer's viewpoint) is given as $b = b_a + b_p$ where b_a is the actual back-order cost to the customer and the customer has to pick the back-order penalty rate (b_p) as part of the incentive for the contractor in the contract design. The minimization problem that must be solved can be described by,

$$\underset{b_p, h_p}{\text{Min}}\ \mathrm{E}\left(\sum_{t=0}^{T} \varphi[x(t), u(t)] + g(T)\right) \tag{19.3}$$

such that

$$\begin{aligned} &\varphi[x(t), u(t)] = Max(hx(t), -bx(t)) + s|u(t)| \\ &x(t+1) = x(t) + u(t) - d(t) \end{aligned}$$

In which $x(t) \in R$ is the quantity of spare parts available in the inventory at time t, for $t = 0$ to T, with $x(t) < 0$ represents a backlog of $|x(t)|$ spare parts. The demand for this component's spare parts at time t is denoted by $d(t)$, which is the stochastic demand for the inventory parts (derived from the failure distribution of the part). The quantity of the spare parts shipped to the inventory at time t is denoted by $u(t)$ with $u(t) < 0$ representing the amount of $|u(t)|$ is shipped back to the factory from the inventory (this particular situation is not allowed in our case). $\varphi[x(t), u(t)]$ is the contractor's cost to operate the inventory given the demand $d(t)$ and order-size $u(\text{t})$. The contractor tries to minimize this cost of operating the service inventory and towards achieving this goal with minimum costs. We also assume that the contractor's shipping costs are fixed and cannot be changed significantly (i.e., there is no uncertainty in it). There is also cost associated with each assessment independent of the inventory size that we reflect in $g(T)$. In this case study, the assessment cost is the cost of testing each torpedo to determine the necessity for repair or replacement.

Assuming the following inputs: $s = 6$(\$/spare), $g = 12$(\$/assessment), $6 < h < 24$(\$/spare/day), $6 < b < 24$(\$/spare/day) and $5 < d(t) < 1000$ number of failures per day, solving for the optimum values of the two contractual parameters of back-order penalty and inventory level incentives, we need to search the entire feasible design space.

To search the design space we use an optimal affine controller developed in [35] to model the optimal decision making of the contractor. This model is well suited to address the correlated-in-time demand distribution to address a general assumption about the common failures in a fleet of systems. The result of this optimization is shown in Fig. 19.7. For example for the case of intervals of 30 days with 12 assessment a year, the expected cost to the contractor is about \$600 per day to support the inventory for the variable number of failures when the assessment cost is low (\$12/assessment). It should be noted that this result is based on the unit of time being 1 day, but the result scales for any unit of time.

In Fig. 19.7, the performance of the contractor over a wide range of parameters and demand is shown. There is an optimal customer assessment interval at which, despite all the uncertainties in failure rate and penalty costs, the cost to the contractor to maintain the inventory availability will be minimized. Also, it can be observed that the contracts in which the contractor performance is being assessed based on a longer time interval (every 60 days) has almost the same performance as when the assessment runs every 20 days when the assessment cost is large. Without any assessment cost there exists a diminishing advantage of performing the assessment on a more frequent basis. The impact of uncertainty in information in different stages

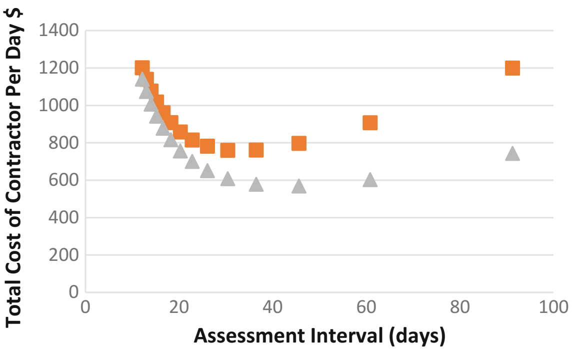

Fig. 19.7 Cost per year using various assessment intervals: *squares-assessment* cost high (\$20/assessment) and *triangles assessment* cost low (\$12/assessment)

of life-cycle can be included within the existing model and a different conclusion could be made for different phases of a contract or life-cycle of a PSS.

One can understand that contractor prefers to undergo a larger assessment interval because: (1) more information is more helpful for demand forecasting in each interval, (2) the effect of one period with lower performance on the overall performance will be minor (total performance measurement is more tolerant towards demand variability), and (3) there is more time and opportunity to compensate a sudden change in demand or a shortcoming in performance.

19.5 Discussion

PSS does not, by itself, ensure that the availability of a system will be guaranteed without designing appropriate contractual requirements. Kashani Pour et al. [31] noted that availability-based contract design has remained mostly unexplored for several reasons: (1) availability-based contracts are relatively new, and cost modeling for this class of contract requires new approach [5]; (2) there is not enough publicly available data to help empirical researchers explore their effectiveness [36]; (3) the engineering design process conventionally does not directly model or utilize the contractual and economic aspects of systems including contractor's incentives and level of effort; and (4) usually sustainment activity problems are divided into sub-problems and solved separately (e.g., supply chain, logistics, and maintenance), which does not utilize the potential advantages of an integrated point of view [37].

In this chapter we explored and demonstrated the core essential elements for the development of informed TES strategies for two classes of PSS that are managed via availability-based contracts. With a systematic and model-based contract design process, not only the pricing and negotiation of the contract requirements can be informed based on the total life-cycle requirements of the PSS; but also, this process can be used to validate the value-added of a variety of technologies including condition monitoring (i.e., CBM and PHM), and obsolescence management.

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