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Availability-Based Real Options Approach to Accurately Determine the Cost and Pricing of Performance-Based Logistic Contracts

By:

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Abstract

Performance-based logistics (PBL) is growing in popularity for both governmental and non-governmental acquisitions of critical systems. These contracts allow the customer to buy the performance of the system rather than purchase the system, and/or to buy the availability of the system rather than pay for maintenance. Outcome-based contracts, which include PBL, are highly quantified "satisfaction guaranteed" contracts where "satisfaction" is defined by the outcomes received from the system, i.e., the specified performance level or availability.

Maintenance planning seeks to predict and optimize when maintenance for a system is performed. Prognostics and Health Management (PHM) provide Remaining Useful Life (RUL) estimates that can be used to plan maintenance. The challenge is how to use the predicted RULs (with their associated uncertainties) and the performance requirements imposed by the outcome-based contracts to optimally plan future maintenance.

This research uses a real options approach to optimize maintenance planning under the constraints imposed by outcome-based contract requirements. A simulation-based real options analysis (ROA) approach is used to determine the optimum predictive maintenance opportunity for a system managed via an outcome-based contract. The methodology is applied to individual systems and fleets of systems, and production and non-production systems.

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Introduction

Background and Motivation

While researchers have studied planning and decision making for outcome-based contracting in different areas (e.g., supply chain, logistics, and inventory management) and for different applications (e.g., defense, avionics, railroads, infrastructure, and energy), there is little formal work dedicated to contractual design and requirements optimization (Kashani-Pour and Sandborn, 2016).

The impact of a contract oriented design processes 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 product and service, called product-service systems (PSSs) (Meier, Roy and Seliger, 2010). 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 (Datta and Roy, 2010). 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 parameters is required (Arora, Chan and Tiwari, 2010). PBL contracting is designed to incentivize this integration towards reducing life-cycle cost and improving design.

System-level PBL contracts were developed to connect system acquisition and logistics with a focus on acquiring a measurable performance outcome (such as the availability of a system) and they seek to optimize system readiness through logistics. Compared with contractor logistics support (CLS), where a contractor rather than the government is responsible for the integration of logistics support functions, an effective PBL requires a balanced contribution from both public- and private-sector providers. PBL contracts, as a group of strategies for system support, are intended to improve system performance at a cost similar to that previously achieved under a non-PBL approach, or obtain the current system performance at a lower cost. The contract structure (defining the desired outcomes), performance measurements, and pricing (payment models) are key parameters in achieving performance-based contract goals throughout the complex legacy system support domain. System-level PBL contracts should address the operational availability time window, reliability, maintainability, supportability, operation and inventory cost, logistics footprint, total cost of ownership, and logistics response time for making program decisions.

An alternative outcome-based contract mechanism called public-private partnerships (PPPs) has been used to fund and support civil infrastructure projects. Availability payment models for civil infrastructure PPPs require the private sector to take responsibility for designing, building, financing, operating, and maintaining an asset. Under the “availability payment” concept, once the asset is available for use, the private sector begins receiving an annual payment for a contracted number of years based on meeting performance requirements (Sharma and Cui, 2012). The challenge in PPPs is to determine a payment plan (cost and timeline) that protects the public interest, i.e., does not overpay the private sector; but also, minimizes the risk that the asset will become unsupported (Gajurel, 2014).

Discrete-event simulation (DES) techniques have been previously used in an integrated model to optimize the *payment* and *contract duration* by incorporating the effects of condition changes, uncertainties, and required availability of infrastructure for PPPs (Sharma, Cui, Chen and Lindly, 2010). This work resulted in obtaining an improved procurement and system acquisition model in which the system availability was chosen as the objective to meet contract requirements (Sandborn, Kashani-Pour, Zhu and Cui, 2014). However, making decisions for specific future actions during pre-project planning (as is done with DES, which is simply an implementation of discounted cash flow analysis) does not accurately address how uncertain conditions evolve because it does not model management flexibility. Real options analysis (ROA) is one means of organizing and valuing flexible strategies to address uncertainties throughout the life cycle of systems. ROA could be used to accommodate management flexibility, and uncertainties in both design and monetary aspects of an outcome-based contract.

System Health Management

The maintenance planning that this report 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) – an RUL is a predicted time to failure. 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 maintenance and allocate maintenance resources. The optimal maintenance planning is modified by performance requirements imposed by the outcome-based contracts.

Maintenance Planning Using Real Options

ROA has been previously applied to maintenance modeling problems. An ROA model for offshore oil platform life-cycle cost-benefit analysis is developed by treating maintenance and decommissioning as real options (Heredia-Zavoni and Santa-Cruz, 2004; Santa-Cruz and Heredia-Zavoni, 2011). Jin, Li, and Ni (2009) presented an analytical ROA cost model to schedule joint production and preventive maintenance under uncertain demands. In the study by Koide, Kaito, and Abe (2001), the maintenance and management cost of an existing bridge for thirty years is analyzed and minimized using ROA. Goossens, Blokland, and Curran (2011) developed a model to assess the differences in performance between different aircraft maintenance operations.

Haddad, Sandborn, and Pecht (2014) applied ROA to estimate the values of maintenance options created by the implementation of PHM in wind turbines. When an RUL is predicted for a subsystem, there are multiple choices for the decision-maker including: performing predictive maintenance at the first maintenance opportunity, waiting until closer to the end of the RUL to perform maintenance, or doing nothing, i.e., letting the system run to failure. Haddad et al. (2014) demonstrated that the fundamental tradeoff in predictive maintenance problems with PHM is finding the point in time to perform predictive maintenance that minimizes the risk of expensive corrective maintenance (which increases as the RUL is used up), while maximizing the revenue earned during the RUL (which increases as the RUL is used up).

Section 2 of this report describes a real options approach to maintenance planning when RULs are predicted for the system. Section 3 presents a case study for a PHM enabled wind turbine with and without an outcome-based contract. In Section 4, we discuss the generalization of the approach developed and demonstrated in Sections 2 and 3 to systems subject to other types of outcome-based contracts (specifically, non-production systems where the outcome is not a quantity, but rather an availability).

Revenue-Earning, Non-Revenue-Earning, Production and Non-Production Systems

Every contract has two sides: the customer who is the recipient of (and pays for) 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. From the customer's viewpoint, there are revenue-earning systems from which the customer derives revenue (the outcome translates into customer revenue); and there are non-revenue-earning systems from which the customer does not derive revenue (the customer's value is mission completion). Revenue-earning and non-revenue-earning are customer distinctions, from the contractor's viewpoint, every contract 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.

An example production system could be a wind farm that is managed under an outcome-based contract called a power purchase agreement (PPA) where the outcome is the amount of energy produced (a quantity). A non-production system could be an aircraft engine where the outcome is the fraction of time that the engine is operational (an availability).

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A Real Options Approach to Maintenance Planning

This section starts by presenting the concept of PHM-enabled maintenance options. Then, it describes 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 offers the flexibility 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 an 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. 2014),

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

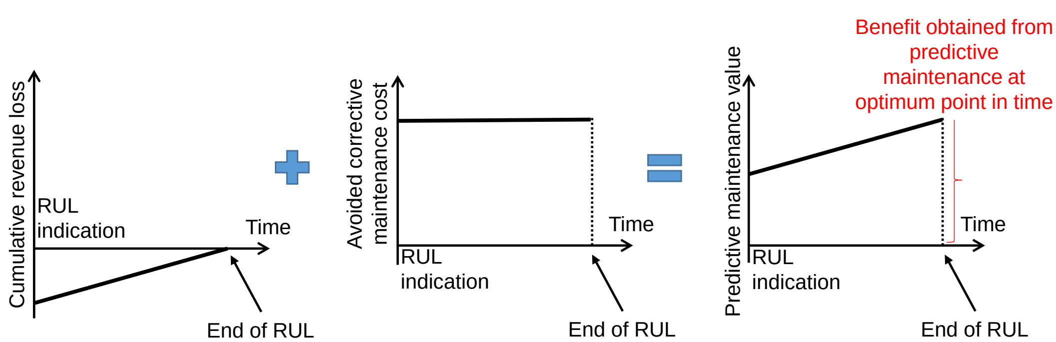

Figure 1 - Predictive maintenance value construction, Lei and Sandborn (2016).

The value from exercising the option is the sum of the cumulative revenue loss and the avoided corrective maintenance cost. 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). Avoided corrective maintenance cost includes:[1] the avoided corrective maintenance parts, service and labor cost, the revenue loss associated with corrective maintenance downtime and the avoided under-delivery penalty due to corrective maintenance (if any).

Figure 1 illustrates the construction of the maintenance value. The cumulative revenue[2] 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 mainenance 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 (Figure 1). 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

[1] 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 Equation (1).

[2] The value construction in this section assumes that the system is a revenue-earning production system, e.g., a wind turbine where the outcome-based contract is based on energy produced. Section 4 presents a generalization of the model that applies to non-production systems.

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.[3] 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.

Due to the uncertainties described above, there are many paths that a system can follow after an RUL indication, as shown in Figure 2. ROA enables us to evaluate the set of possible paths to determine the optimum time to take action.

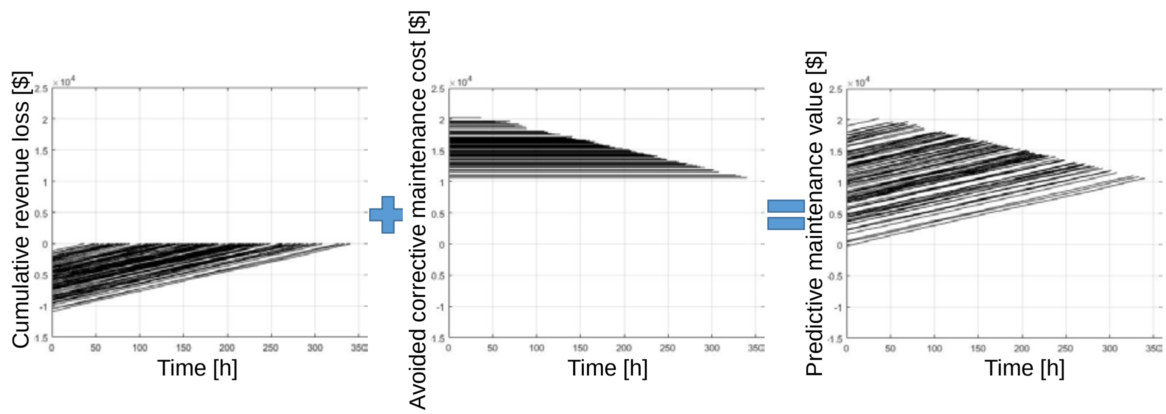

Figure 2 - Example of the simulated paths after an RUL indication.

Consider the case where predictive maintenance can only be performed on specific dates.[4] 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[5]). This

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

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

[5] 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-style option as has been demonstrated and solved by Haddad et al. (2014). The Haddad et al. (2014) solution 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-style option.

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 Figure 3 shows two example predictive maintenance paths (diagonal lines) and the predictive maintenance cost (the cost of performing the predictive maintenance). ROA is performed to valuate the option where the predictive maintenance option value, O_{PM} is given by

$$O_{PM} = Max(V_{PM} - C_{PM}, 0) \tag{1}$$

where V_{PM} is the value of the path (right most graph in Figure 2 and the diagonal lines in Figure 3), 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 Figure 3 are shown on the right side of Figure 3. Note that there are only values of O_{PM} plotted at the maintenance opportunities (not in between the maintenance opportunities). Equation (1) 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 Lei and Sandborn (2016).

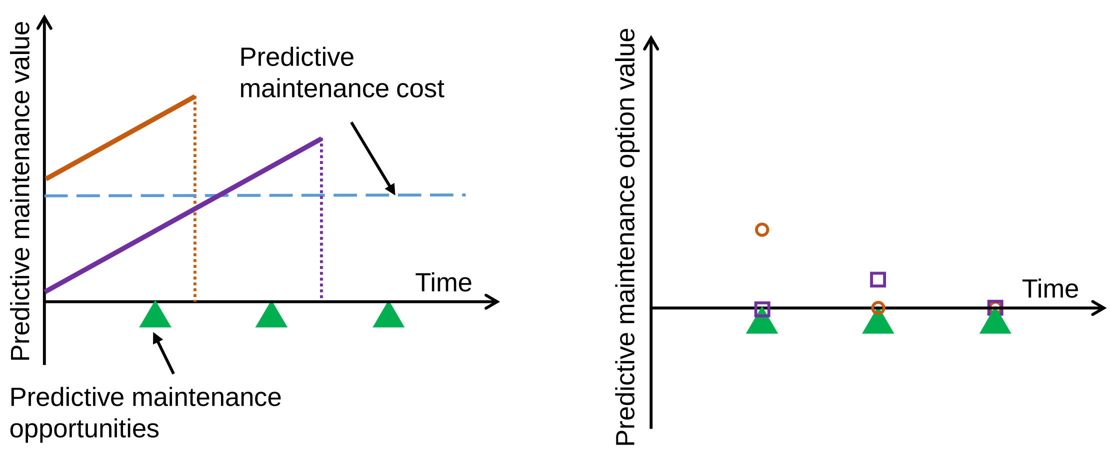

Figure 3 - ROA valuation approach - the circles and squares in the right graph correspond to the upper path and the lower path in the left graph, respectively.

Maintenance Planning for Production Systems

An outcome-based contract (such as PBL) 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 outcome target, payment schedule before and after that target is reached (generally the latter is lower than the former), penalization mechanisms, the outcome already produced, and the operational state of the other systems in the population.

Incorporating Outcome-Based Contract Requirements into the Predictive Maintenance Option

Assume that all systems are operational. Assume in this case the population of systems can meet the outcome 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-outcome-based contract, since the cumulative revenue loss will be lower (because the price paid for the outcome 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 an under-delivery penalty would occur, and the avoided corrective maintenance cost will be higher than the non-outcome-based contract (as delivered) case that doesn't have any penalization mechanisms.

Under an outcome-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.

Case Study – Maintenance Planning for a Wind Farm with an Outcome-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 outcome-based contract. A Vestas V-112 3.0 MW offshore wind turbine (Vestas, 2013) was used for this study.

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 4 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 the 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 Figure 4 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 PPAs. A PPA defines the energy delivery targets, purchasing prices, output guarantees, etc. Wind farms are typically managed via PPAs for several reasons (Bruck, Goudarzi and Sandborn, 2016). First, though power can be sold into the spot market, the average spot market prices tend to be lower than long-term PPA contract prices. Second, lenders are not willing to finance wind farm projects without a signed PPA that secures a future revenue stream. Third, wind energy buyers prefer simply purchasing power to owning and operating wind farms by themselves.

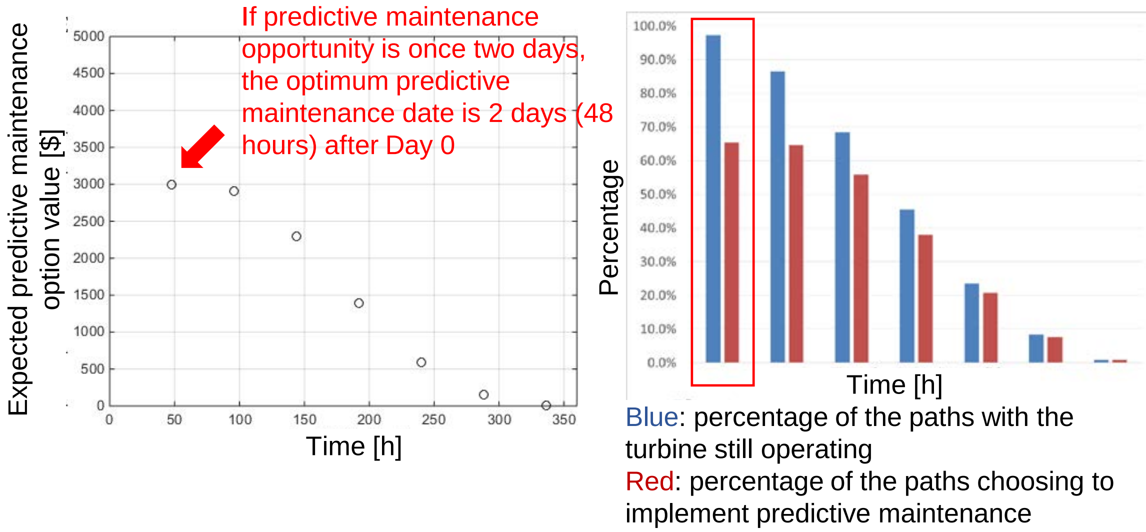

Figure 4 - Optimum maintenance date after an RUL indication for a single wind turbine.

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 the wind farm is expected to generate during the whole year, which is used to define annual energy delivery target. For each year, a maximum annual energy delivery limit can be set, beyond which a lower excess price may apply. The buyer may also have the right to refuse 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 & 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 Lei and Sandborn (2017) 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 Figure 5.

ROA run on the wind farm under a PPA demonstrates that the maximum maintenance value varies with the number of turbines that are down (non-operational). Figure 6 shows the results. The result that corresponds to Figure 5 is the 0-turbine down case in Figure 6.

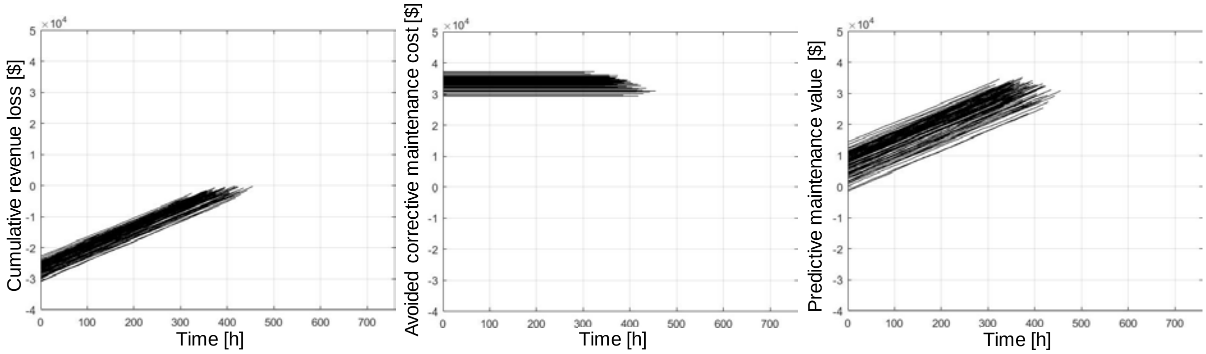

Figure 5 - Combined value paths for turbines 1 and 2 in a 5-turbine-farm managed by PPA.

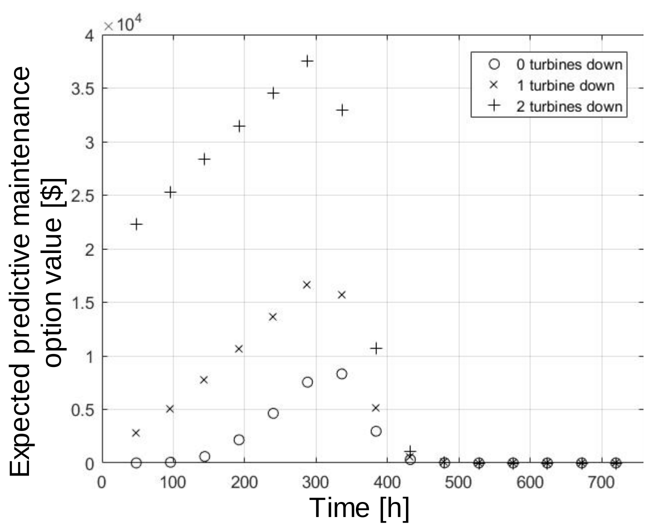

Figure 6 - Optimum maintenance opportunity determined by the ROA approach for turbines 1 and 2 in a 5-turbine-farm managed by a PPA.

Maintenance Planning for Non-Production Systems

The real options approach for the predictive maintenance planning described in Sections 2 and 3 assumes that the system is revenue earning, e.g., a wind turbine. In this Section a generalization of the model is developed and applied to the non-production systems. For example, the hourly rate (e.g., per available hour) in PBL contracts is a fixed number. Hence, it creates a different challenge than selling the energy, which produces a variable amount of revenue.

Maintenance Planning for a Single Non-Production System

In this section, a generalization of the model is developed and applied to the non-production systems. To begin with, we assume a single system (e.g., an aircraft engine) with embedded PHM. This system is managed under an outcome-based contract between a contractor (e.g., the OEM of the engine) and a customer (e.g., an airline or a military organization), in which the availability is the contracted for measurable performance outcome. The customer pays a fixed contract price to the contractor for each unit of time the system is operating; the contractor compensates the customer for each unit of time the system is down (non-operational). The contractor is responsible for all the maintenance activities. An availability target is set in the contract, and if the actual availability is lower than the target, a penalty on the contractor is calculated as the difference between the availability target and the actual availability multiplied by a fixed penalty rate. On Day 0, an RUL with associated uncertainties is predicted for the engine and the contractor needs to decide if and when to implement the predictive maintenance; alternatively, the system will be operated until failure at which point corrective maintenance will be performed (we assume that safety is not compromised and therefore is not addressed in this analysis). It is reasonable to assume that the predictive maintenance will cause a lower cost (part, service, labor, etc.) and shorter downtime than a corrective maintenance activity.

The cumulative revenue loss, the avoided corrective maintenance cost and the predictive maintenance value paths can be simulated as shown in Figure 7. As shown in the left plot, the cumulative revenue loss paths start at different points on the vertical axis, because the longer the RUL is, the more cumulative revenue will be lost if predictive maintenance is implemented, and the lower the path's initial value is. All the cumulative revenue loss paths are ascending over time, because the later the predictive maintenance is performed, the less cumulative revenue will be lost. The cumulative revenue loss paths terminate at different time points due to the uncertainties in the RUL prediction. In the middle plot in Figure 7, each avoided corrective maintenance cost path is constant over time. However, the later the predictive maintenance is carried out, the longer the system will operate, and therefore the availability penalty is lower. By combining the cumulative revenue loss and the avoided corrective maintenance cost paths, the predictive maintenance value paths shown in the right plot in Figure 7 are obtained.

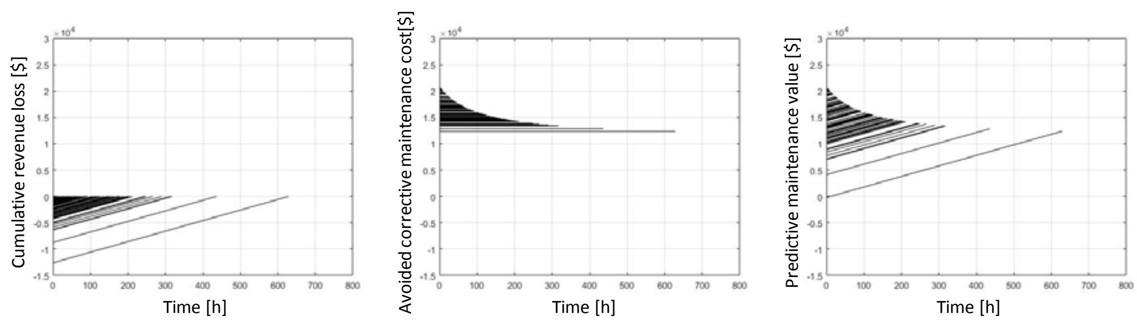

Figure 7 - Example of the simulated paths after an RUL indication for a single non-production system managed under an outcome-based contract.

By applying a real options analysis (ROA) approach, the optimum predictive maintenance opportunity can be determined as shown in Figure 8.

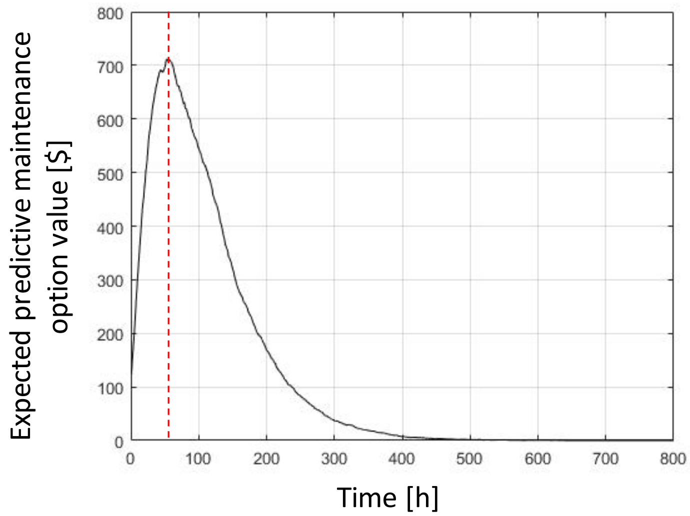

Figure 8 - Optimum maintenance opportunity determined by the ROA approach (red dash line).

Incorporating Inventory and Mission Time Window Constraints

In this section, the inventory of spares and the mission time window are integrated into the non-production system maintenance option valuation model, which will influence the decision to act on PHM, i.e., RUL predictions. Note, the inclusion of the spares inventory and mission window can also be applied to the production system model.

Inventory modeling is an important part of the integration of PHM and inventory management. However, most of the existing models do not consider the best time to perform maintenance (they only consider the inventory size). The model discussed here, addresses the best time to perform maintenance. The goal of this model is “when-to-act” rather than “how many spare parts to order”. This assumption allows this model to be extended to the case of multiple systems using a single shared inventory (e.g., a fleet of aircraft all drawing engines from the same inventory).

The decision to act on RUL predictions will be influenced by the inventory of spares that are available. An integrated model to address both PHM and inventory is described here. This integration clarifies how PHM should be used to make maintenance and logistics decisions, and how it impacts inventory management. Here, the primary focus is on individual component prognosis (e.g., an aircraft engine is considered to be an individual component for the purpose of this discussion) and the system-level maintenance support and management decision. This model simulates the case where upon an RUL indication, the spare part is not available and it takes some time to become available (the amount of time to become available is assumed to be known). In this case, if the maintenance starts at a point in time before the spare part arrives, a penalty on the contractor will occur (e.g., to expedite the spare order).

The cumulative revenue loss, the avoided corrective maintenance cost and the predictive maintenance value paths can be simulated as shown in Figure 9. The avoided corrective maintenance cost in the middle plot and the predictive maintenance value paths in the right plot separate into two groups. The higher group represents the penalty for implementing corrective maintenance before the inventory is replenished; while the lower group represents the penalty for implementing corrective maintenance after the inventory is replenished. By applying the ROA approach, the optimum predictive maintenance opportunity can be determined as shown in Figure 10.

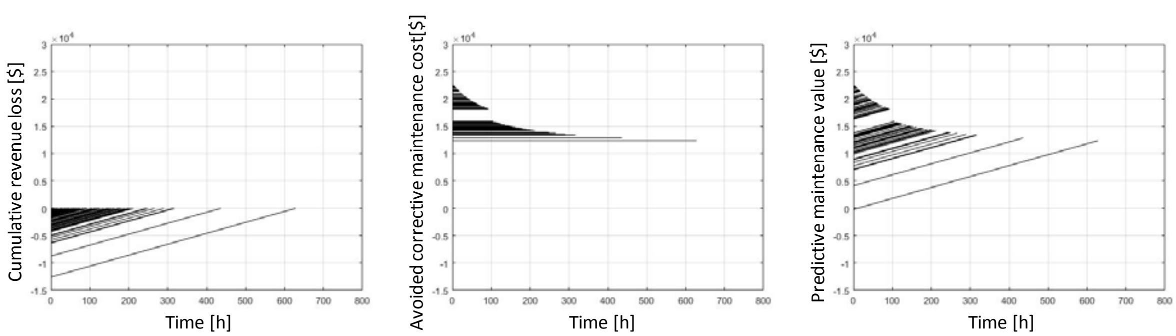

Figure 9 - Example of the simulated paths after an RUL indication for a single non-production system managed under an outcome-based contract.

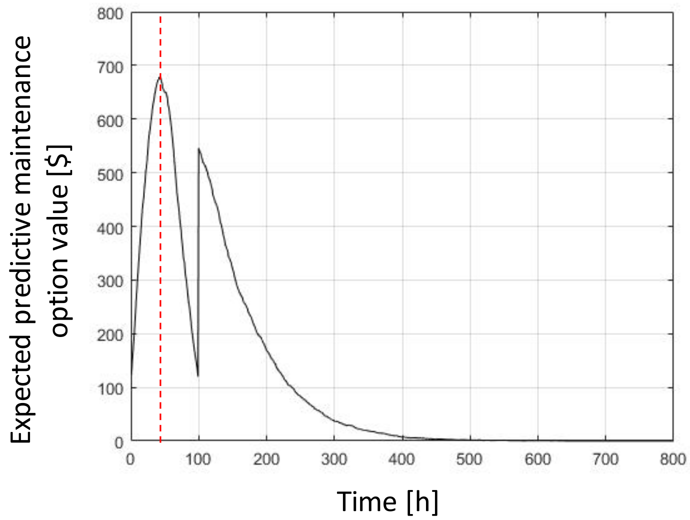

Figure 10 - Optimum maintenance opportunity determined by the ROA approach with the inventory considered (red dash line).

The mission time window is another important factor that can affect the maintenance decision based on PHM information. It is assumed that the mission accomplishment is of significant importance to the customer, and the upcoming mission time window is known. According to the contract, if the downtime of the scheduled maintenance event and the mission time window overlap, the contractor has to compensate the customer for the overlapping time, calculated as the length of time multiplied by a fixed penalty rate. The cumulative revenue loss paths, the avoided corrective maintenance cost paths, and the predictive maintenance value paths can be simulated as shown in Figure 11. The optimum predictive maintenance opportunity can be determined as shown in Figure 12. Compared with Figure 7, in the middle plot of Figure 11, some paths with long RULs have higher avoided corrective maintenance costs, because for those paths the corrective maintenance downtime partially or completely overlaps the mission time window leading to a high penalty.

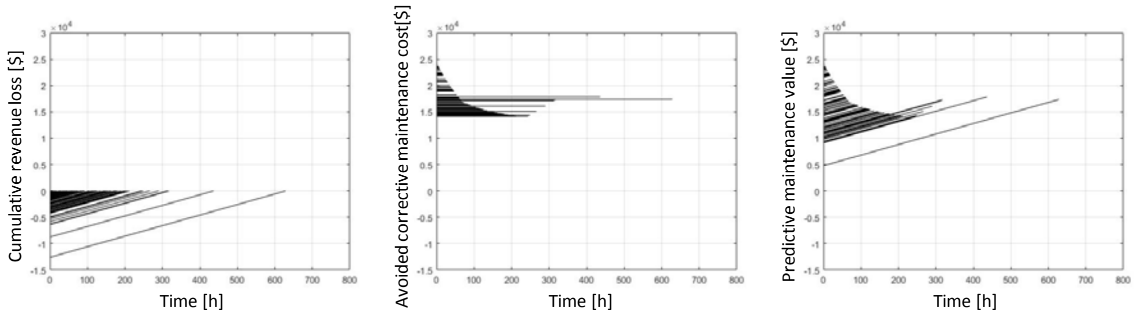

Figure 11 - Example of the simulated paths after an RUL indication for a single non-production system managed under an outcome-based contract with the mission time window considered.

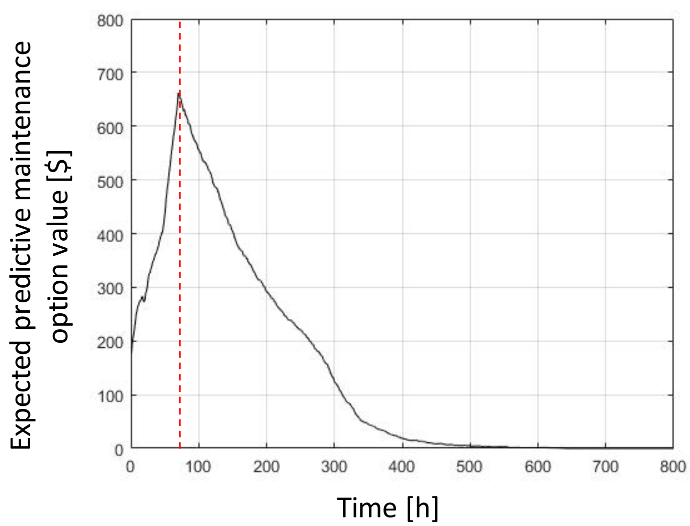

Figure 12 - Optimum maintenance opportunity determined by the ROA approach with the mission time window considered (red dash line).

If both the inventory and the mission time window are considered concurrently, the values paths and the optimum predictive maintenance opportunity are shown in Figures 13 and 14. In Figure 14, the optimum predictive maintenance opportunity is when the inventory will be replenished (100 hours after the RUL indication, indicated by the red line in Figure 14).

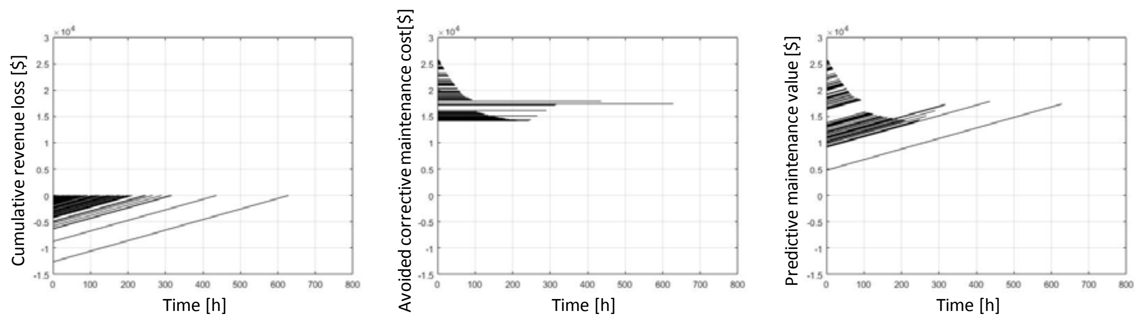

Figure 13 - Example of the simulated paths after an RUL indication for a single non-production system managed under an outcome-based contract with both inventory and mission time window considered.

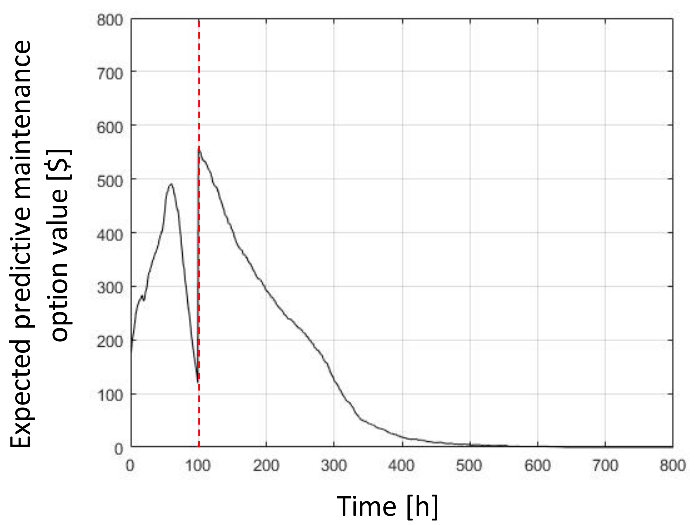

Figure 14 - Optimum maintenance opportunity determined by the ROA approach with both inventory and mission time window considered (red dash line).

Maintenance Planning for a Non-Production System Fleet

When we consider a fleet of systems under an outcome-based contract, both the cumulative revenue loss and the avoided corrective maintenance cost paths for the systems with RULs will be influenced by the contract price, availability requirement, penalization mechanisms, and the operational state of the other systems in the fleet.

Now we assume a fleet including five systems with embedded PHM are managed under an outcome-based contract, and the availability is the measurable performance outcome. The customer pays a fixed contract price to the contractor for each unit of time of each system operating; the contractor compensates the customer for each unit of time of each system down. The contractor is responsible for all the maintenance activities. An availability target is set in the contract, calculated in a time window from Day 0 to when the last predictive or corrective maintenance event finishes, in which the total uptime and downtime of all the five systems will be summed to calculate the actual availability. If the actual availability is lower than the target, a penalty on the contractor will be calculated as the difference between the availability target and the actual availability multiplied by a fixed penalty rate. On Day 0, RUL predictions with associated uncertainties are predicted for two of the systems (the other three systems have no predicted RUL and are operating normally), and the contractor needs to decide if and when to implement the predictive maintenance. It is assumed that the contractor is willing to carry out predictive maintenance on all the turbines with RUL predictions during a single visit. Once the first failure (either one of the two systems with RUL predictions) happens, all the systems with RUL predictions (one other system in this case) will be operated until failure and corrective maintenance will be performed.

If neither the inventory nor mission time window constraints exist, the cumulative revenue loss, the avoided corrective maintenance cost, and the predictive maintenance value paths for the two systems with RUL predictions in the five-system fleet can be simulated as shown in Figure 15. All the cumulative revenue loss paths start at different points on the vertical axis, ascend over time, and terminate at different time points, representing the uncertainties in when the first system failure happens. By combining the cumulative revenue loss and the avoided corrective maintenance cost paths, the predictive maintenance value paths shown in the right plot in Figure 15 are obtained. By applying a ROA approach, the optimum predictive maintenance opportunity can be determined as shown in Figure 16.

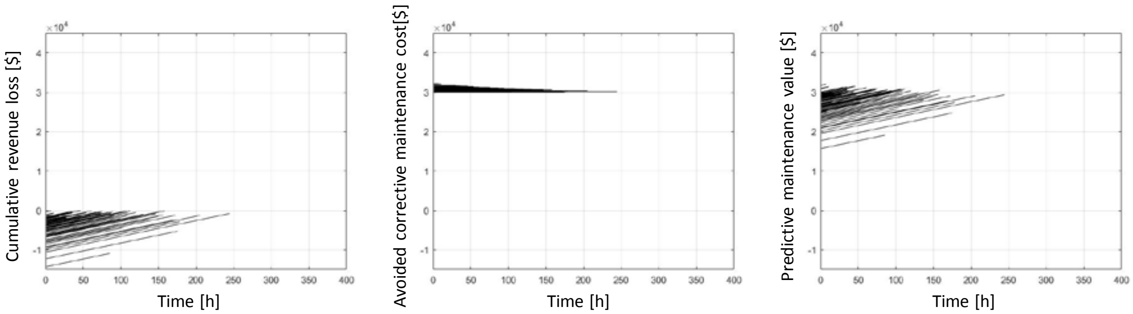

Figure 15 - Example of the simulated paths for two systems with RUL predictions in a five-system fleet managed under an outcome-based contract.

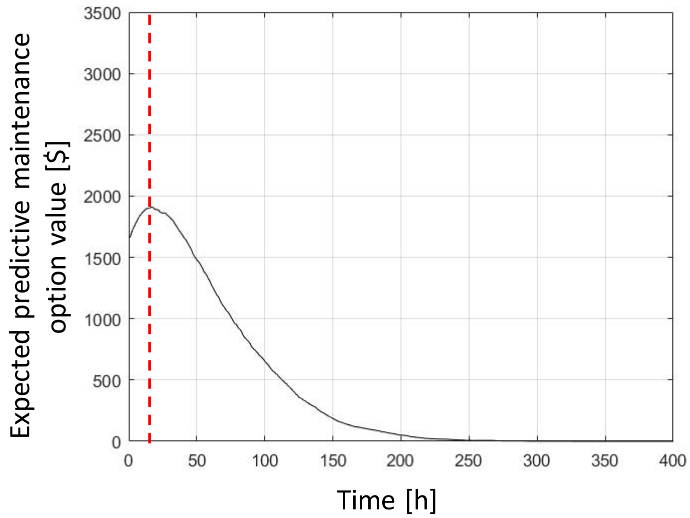

Figure 16 - Optimum maintenance opportunity determined by the ROA approach for two systems in a five-system fleet with RUL predictions (red dash line).

Now we assume no spare parts are not available at Day 0, and it takes a known time for the inventory to be replenished (two spares to be obtained). In this case, if the maintenance starts at a time point before the spare parts arrive, a penalty on the contractor will occur. The cumulative revenue loss, the avoided corrective maintenance cost and the predictive maintenance value paths can be simulated as shown in Figure 17. The avoided corrective maintenance cost in the middle plot separate into three groups. The higher group represents the penalty for implementing corrective maintenance on the two systems before the inventory is replenished; the middle group represents the penalty for implementing corrective maintenance on one system before and the other after the inventory is replenished; while the lower group represents the penalty for implementing corrective maintenance on both systems after the inventory is replenished. By applying the ROA approach, the optimum predictive maintenance opportunity can be determined as shown in Figure 18.

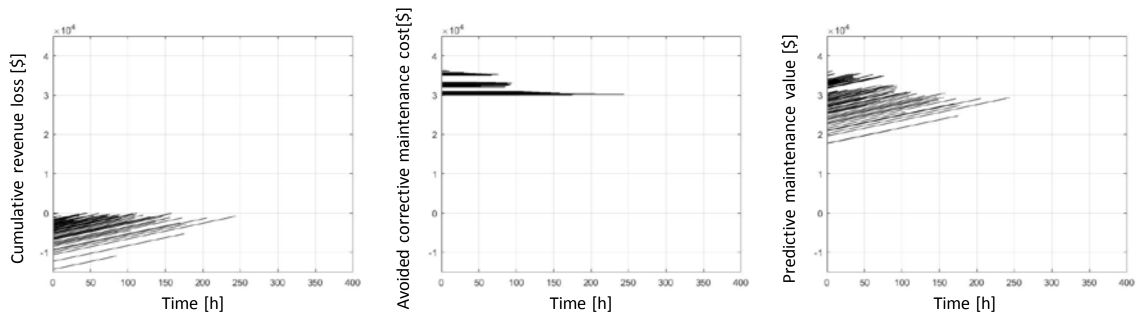

Figure 17 - Example of the simulated paths after for the two systems with RUL predictions in a five-system fleet managed under an outcome-based contract with the inventory considered.

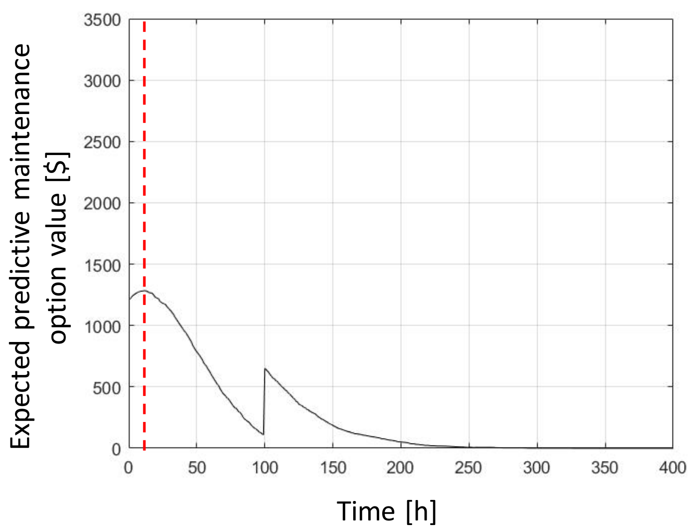

Figure 18 - Optimum maintenance opportunity determined by the ROA approach for the two systems with RUL predictions in a fleet of five system with the inventory considered (red dash line).

If the mission time window constraint exists, the cumulative revenue loss, the avoided corrective maintenance cost and the predictive maintenance value paths can be simulated as shown in Figure 19, and the optimum predictive maintenance opportunity can be determined as shown in Figure 20. Compared with Figure 15, in the middle plot of Figure 19, some paths have higher avoided corrective maintenance costs, because for those paths the corrective maintenance downtime partially or completely overlap with the mission time window (leading to a high penalty).

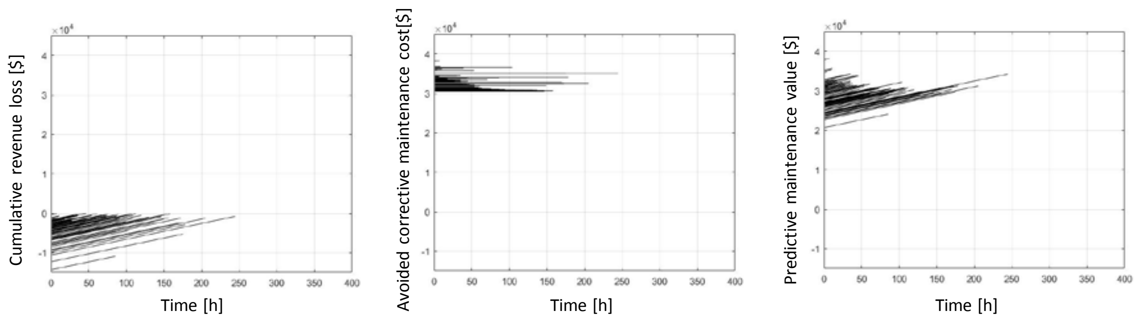

Figure 19 - Example of the simulated paths after for the two systems with RUL predictions in a five-system fleet managed under an outcome-based contract with the mission time window considered.

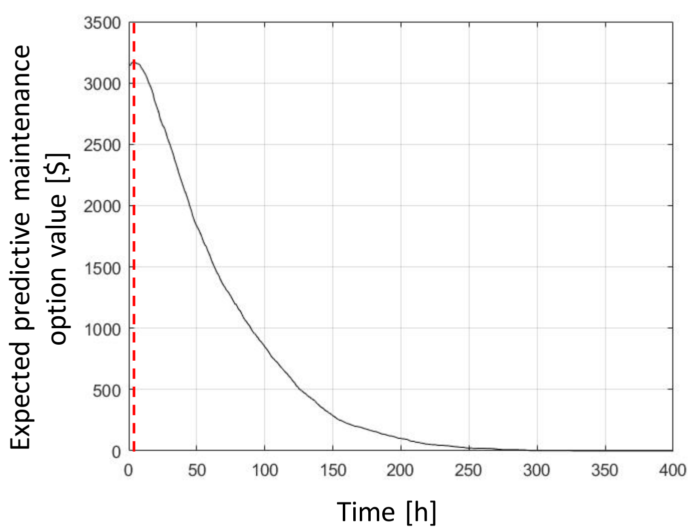

Figure 20 - Optimum maintenance opportunity determined by the ROA approach for the two systems with RUL predictions in a five-system fleet with the mission time window considered (red dash line).

If both the inventory and the mission time window are considered concurrently, the values paths and the optimum predictive maintenance opportunity are shown in Figures 21 and 22.

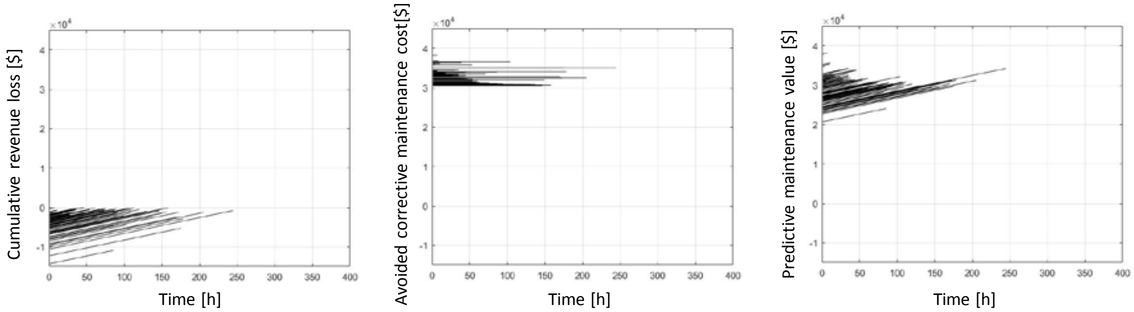

Figure 21 - Example of the simulated paths after for the two systems with RUL predictions in a five-system fleet managed under an outcome-based contract with both inventory and mission time window considered.

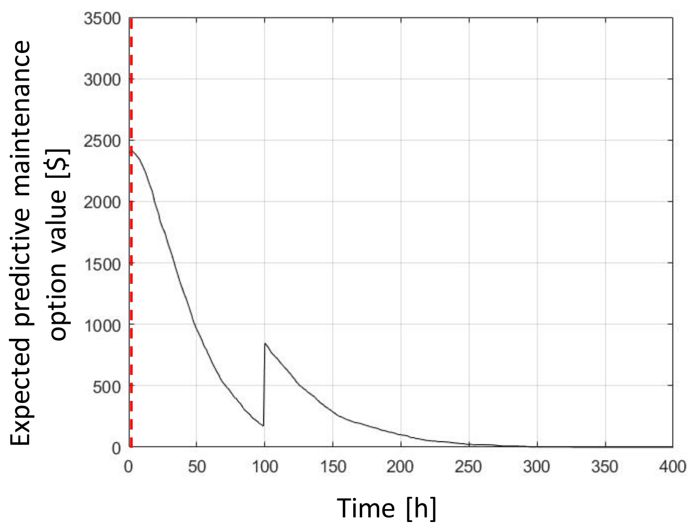

Figure 22 - Optimum maintenance opportunity determined for the five-system fleet by the ROA approach with both inventory and mission time window considered (red dash line).

Maintenance Planning for a Single Non-Production System - An Infinite-Horizon Model

Cumulative revenue loss is one way to model the value of the portion of the RUL thrown away by implementing predictive maintenance. This value takes the form of loss in spare part inventory life (i.e., the revenue earning time for the system will be shortened by predictive maintenance when compared with corrective maintenance, because some inventory life has been disposed of). However, for some systems the number of spares may not be a constraint (i.e., the revenue earning time period for the system will still be the same by experiencing more predictive maintenance events than corrective maintenance events), therefore the cumulative revenue loss may not be a suitable indicator of the value of the portion of the RUL thrown away by predictive maintenance. In this case, compared with the corrective maintenance, predictive maintenance will lead to more cumulative revenue (called extra cumulative revenue gained) because it will generally cause shorter downtime, however it will also lead to more future predictive maintenance events (which will negatively affect the avoided maintenance cost). Therefore, the cost of extra future predictive maintenance events caused by a predictive maintenance event can be used to model the value of the portion of the RUL thrown away.

Assume that a single non-production system is operating with an infinite horizon[6] (which excludes the impacts of the initial condition and the final condition). To compare this new approach with the approach introduced in Section 4.1, assume there are no constraints on the availability, inventory or mission time window. The extra cumulative revenue gained, avoided maintenance cost and predictive maintenance value (sum of the aforementioned two items) paths for a single non-production system can be simulated as in Figure 23. As a contrast, the cumulative revenue loss, avoided corrective maintenance cost and predictive maintenance value paths for the same system can also be simulated as in Figure 24. By applying

[6] Infinite-horizon means that the system considered does not have a predetermined time of extinction. Incorporating an arbitrary finite horizon can introduce end-of-study distortions. Infinite-horizon problems are therefore typically modeled over an unbounded horizon. Infinite-horizon also ignore the initial conditions on the system and assume that the system has reached a steady-state, which may be either stationary or non-stationary.

the ROA approach, the optimum predictive maintenance opportunities can be determined separately as shown in Figures 25 and 26. As can be seen, the two approaches are suggesting different optimum predictive maintenance opportunities.

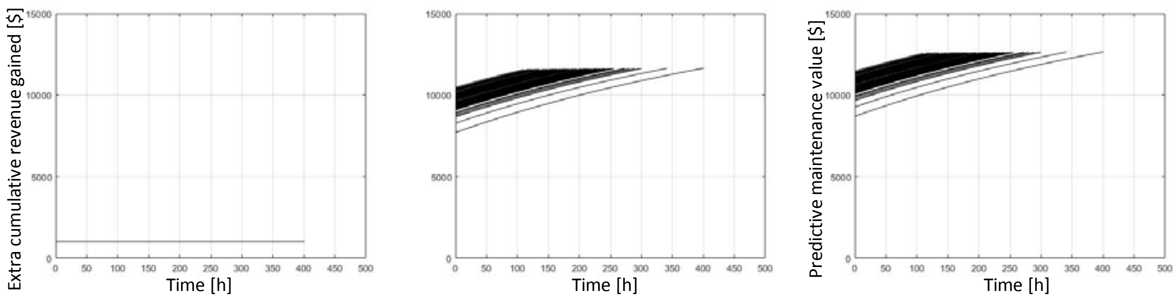

Figure 23 - Example of the simulated extra cumulative revenue gained, avoided maintenance cost and predictive maintenance value paths.

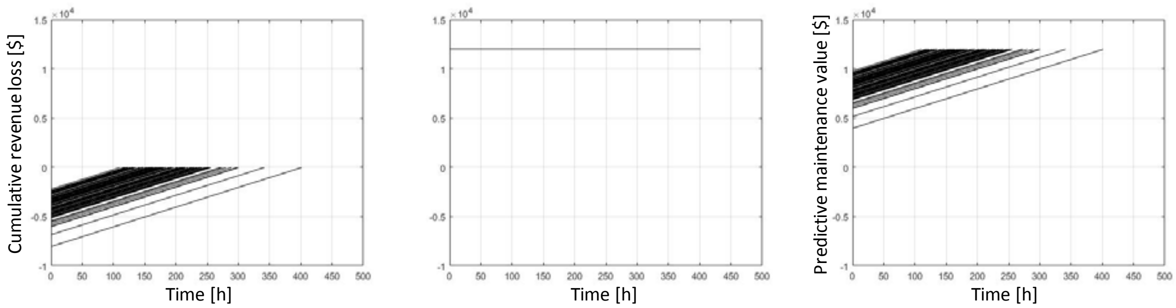

Figure 24 - Example of the simulated cumulative revenue loss, avoided corrective maintenance cost and predictive maintenance value paths

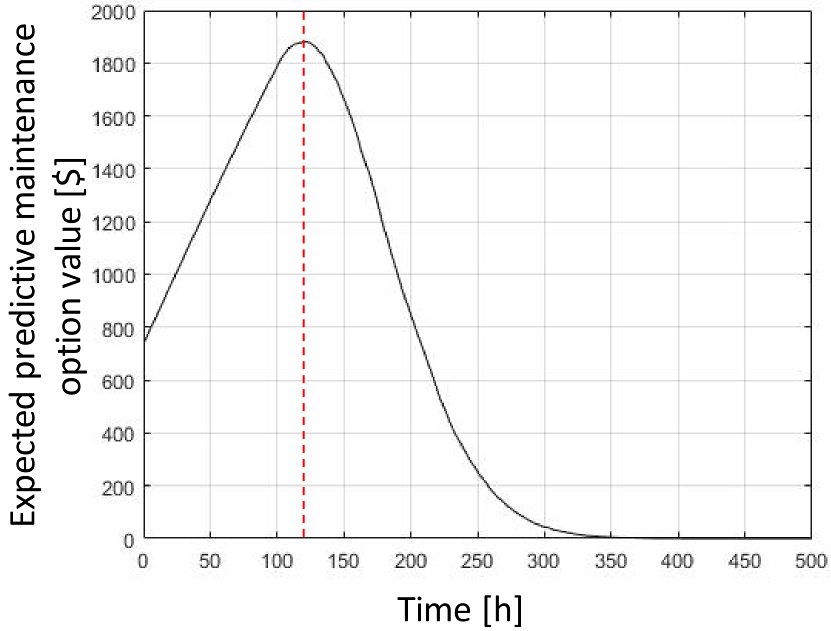

Figure 25 - Optimum maintenance opportunity determined for Figure 23 (red dash line).

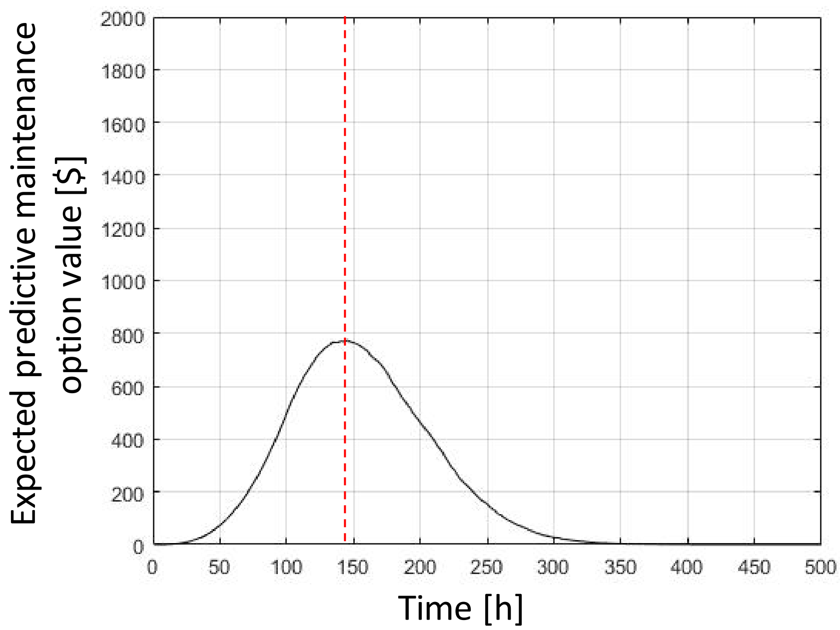

Figure 26 - Optimum maintenance opportunity determined for Figure 24 (red dash line).

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Conclusions

The objective of this work is to find the optimum predictive maintenance opportunity for systems managed under outcome-based contracts. Uncertainties in the RUL predictions from PHM and other sources are considered. This work demonstrates that the optimum action to take when a system presents an RUL depends on whether the system is an individual or is part of a larger population of systems managed via an outcome-based contract.

When considering non-production systems, the availability of a required spare part in the inventory is added to the model and both the inventory and PHM are taken into account when making the decision on best time to perform maintenance.

Our vision is to develop a multidisciplinary outcome-based real options pricing model for supply chain and logistics design to determine the optimum performance metrics and an optimum payment plan (amount, term, incentive fees, and penalties) during the total life cycle of critical systems in PBL contracts. The proposed integrated PBL contract would address public policy and management in the field of government acquisition; it is also applicable to many types of non-governmental performance-based contracts. It includes economics, financial management, risk management, marketing, contracting, logistics, test and evaluation, and systems engineering management.

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