# Using Real Options to Manage Condition-Based Maintenance Enabled by PHM

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***Abstract*—This work proposes a new economic approach that can form a cost-benefit-risk basis for optimum decision making for systems with prognostic capabilities, and a method to assess the value of PHM for its user after a prognostic indication. PHM potentially enables performance based logistics, condition-based maintenance, and reduced life cycle cost. When an anomaly is detected in a system, and the remaining useful life is estimated, the user has to make a decision about how to operate or manage the system given a set of constraints or requirements (e.g., to maximize availability). This paper proposes a new economic basis for evaluating the flexibility enabled by prognostic and health management systems. The proposed framework is based on Real Options theory for valuating the options arising through the use of PHM. In the context of PHM an option represents the purchase of an opportunity to take a particular action in the future. The underlying assets are not tradable securities (as they would be in financial options), but rather, they are cost avoidance opportunities or mission values. We provide two potential applications to illustrate the new model for electronic systems in a commercial aircraft used by a commercial airline, and wind farms.**

***Keywords-component; decision support system; maintenance optimization, real options; economic analysis; post-prognostic indication; PHM; CBM; avilability***

## I. Introduction

Prognostics and health management (PHM) is discipline consisting of technologies and methods to assess the reliability of a product in its actual life cycle conditions to determine the advent of failure and mitigate system risks [1][2]. It is a technology that allows complex systems to shift from traditional maintenance (scheduled or unscheduled) to condition-based maintenance (CBM). PHM is an enabler of performance-based contracts and potentially reduces life-cycle cost. When an anomaly is detected in a PHM-enabled system, and the remaining useful life (RUL) of the system is estimated, the decision maker is then faced with multiple choices called options, which can be exercised to manage the health of the system. An 'option' is a right, but not an obligation to take a particular action in the future [3]. Existing work on health management for systems with prognostic capabilities addresses the enterprise level (a fleet of systems) and the system level (individual system instances). In broad terms, the former focuses on the use of PHM to perform logistics planning, availability optimization and on building business cases to justify the implementation of PHM across an enterprise, and the latter focuses on fault accommodation and isolation to ensure mission success, and failure avoidance.

This paper provides a new economic basis to manage the flexibility (e.g., when to perform maintenance after a prognostic indication) enabled by PHM systems using Real Options (RO) theory. It addresses a gap in health management for systems with PHM by addressing the economic aspect after a prognostic indication. We also attempt to link high-level requirements (such as an availability requirement from the customer) and low-level requirements such the performance of the prognostic algorithm [4].

Systems incorporate PHM for a number of reasons that include: failure avoidance, life cycle cost reduction, warranty verification, future system design improvements, and availability improvement. One very common PHM driver is availability (which is reflected into safety and life cycle cost). For example, the value of safety and infrastructure critical systems such as avionics systems and wind farms is associated with their availability. Availability is the ability of a service or a system to be functional when it is requested for use or operation [5]. Commercial airlines go out of business if their planes are not available to fly; 911 systems are useless if they are not available when people call them; and wind farms cannot be depended on for energy generation if they are always down waiting for maintenance. Availability of a system is a function of its reliability and how efficiently it can be maintained. There are different approaches to maintenance, but fundamentally, depending on if a system has failed, when we think it will fail, how it has failed, etc., there are decisions that need to be made about how to and when to maintain it.

A simple motivating example would be an aircraft flying between two locations. A prognostic indication is obtained at a certain time during the flight. The decision-maker has a set of options amongst which they can choose. The term options will be used in the remainder of the paper to denote a choice or action the decision maker can take after a prognostic indication. Fig. 1 shows a general diagram for options arising after prognostic indication. Not all systems have all the options shown in Fig. 1 available to them.

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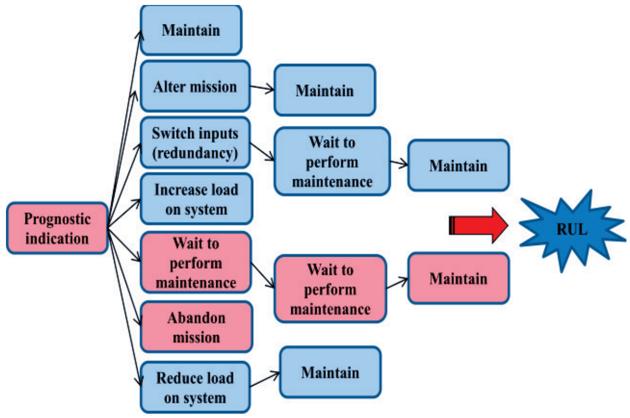


Figure 1- Options arising post-prognostic indication

If a value, or valuation, of each one of the options can be established, the appropriate health management decisions can be performed at the system-level. Furthermore, the approach can be extended to optimize health management decisions at the enterprise-level. Consider a wind farm example; assuming that a farm has 10 turbines with prognostic capabilities each having a different remaining useful life (RUL). RUL is treated as a deterministic number in this example for the purpose of illustration. Fig. 2 shows the RUL for each of the turbines of such as farm.

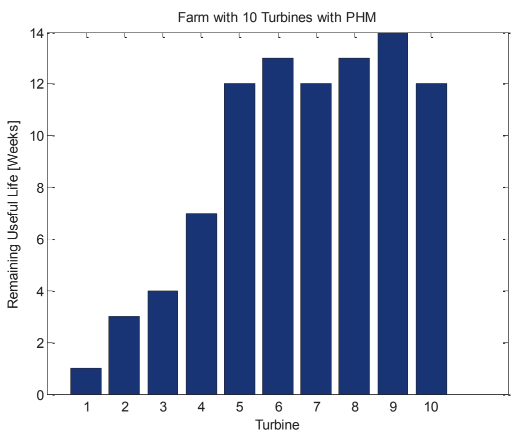


Figure 2- Turbines with different prognostic indication

Maintenance for offshore wind farms requires non-traditional resources such as vessels with cranes. The availability of these resources to perform maintenance is not continuous, e.g., adverse weather conditions may make it impossible to maintain the turbines. Health management and maintenance optimization has been raised as a key point for research in multiple research efforts associated with off-shore wind farms [6] and [7]. For instance, taking a maintenance vessel to the offshore farm may be very costly, so when a vessel is at the farm to perform maintenance the decision-maker is faced with the option to maintain multiple turbines at once (on those that have failed and those indicating a small RUL) since the vessel may not be available for maintenance for an extended period of time. If wind turbines become non-operational between maintenance visits, then availability of energy from the farm suffers. The proposed approach will assist in answering questions such as which turbines to maintain now if the vessel is on site for maintenance, and which turbines should be maintained next time the vessel is at the farm. Hence assessing the value of waiting to perform maintenance can be a driver for maintenance planning for systems in order to minimize cost while maintaining a required level of availability.

The paper is structured as follows: Section II introduces the flexibility induced by PHM. Section III introduces real options formally as a way to manage flexibility, along with the suitable valuation models for the PHM problem. Section IV presents potential applications of the proposed approach. Section V provides a summary, potential value of the proposed approach, and the future work on the subject.

## II. Flexibility Induced by PHM

This section summarizes the cost-avoidance obtained from PHM implementation. Maintenance optimization is discussed, and flexibility induced by PHM is discussed.

### *A. Cost-Avoidance Opportunities Created by PHM*

PHM has been shown to be beneficial for the health management of systems, and potentially provides a number of benefits (defined as cost avoidance opportunities) including, [1], [5]and [8]:

- Avoiding failures
  - Minimizing the cost of unscheduled maintenance
  - Increasing availability
  - Reducing risk of loss of system
  - Increased human safety
- Minimizing loss of remaining life
  - Minimizing the amount of remaining life thrown away by scheduled maintenance actions
- Logistics (reduction in logistics footprint)
  - Better spares management
  - Optimization of resource usage
- Improved repair
  - Better diagnosis and fault isolation
  - Reduction in collateral damage during repair
- Reduction in redundancy (possible in the long term)
- Reduction in no-fault-founds

### *B. Maintenance Optimization*

Maintenance optimization is a process that attempts to find the best balance of the maintenance requirements (contractual, economic, technical, etc.) and the resources used to carry out the maintenance program (people, spares, consumables, equipment, facilities, etc.) [9]. When maintenance optimization is effectively implemented it will: improve system availability, reduce overall maintenance cost, improve equipment reliability, and improve system safety. In this work, we refer to maintenance optimization at the system level and the enterprise level. In the former case, optimization is performed to choose the option that generates the largest cost avoidance and or maximizes the availability for an individual system. In the latter, optimization is performed to choose the optimal subsystems to be maintained and meet availability at the enterprise level. We note that availability requirements may be different at the two levels: a wind farm may still be able to deliver a required amount of energy even if a turbine is down.

CBM has been shown to be an effective way of managing the health of systems. However, CBM has drawbacks. This may be due to seemingly contradictory and changing requirements from operations as well as maintenance for a multitude of different systems within strict time constraints [11]. Hence the optimization of the particular subsystems when the system is down for maintenance is a crucial task that needs to be addressed. Previous work for optimizing CBM is generally referred to as work scope optimization. These methods are essentially multi-objective optimization models that attempt to choose the subsystems to be maintained at every maintenance event given the users requirements and a set of constraints. Impact Technologies (LLC) [10] developed software for work scope optimization for engines. Their architecture provides guides to maintainers in developing the optimal work scope to correct primary failures on engines and identifies additional opportunistic actions that would reduce cost and increase availability by assessing the remaining useful life of components and performance characteristics. Iyer et al. [11] propose a work scope optimization model that is comprised of a multi-objective problem subject to a number of constraints, after a prognostic indication. The framework proposed in [11] seeks to look at the Pareto frontier for the solution. Other research studying CBM optimization can be found in [12]. The work reported in this paper differs from the above-mentioned work by providing a new economic basis to assess the value of options which can be used to manage the health of systems.

### C. Flexibility Induced by PHM

The RUL estimation provided by the PHM system is the driver for most benefits or cost avoidances listed in Section II.A. RUL is the remaining useful life that a system has and it effectively represents the lead time (subject to appropriate uncertainties) for the decision-maker or other maintenance entities to take preventive actions prior to a failure. *This can be described as a flexibility phenomenon whereby entities involved with the operation, management, and maintenance of a system have the flexibility to take actions at any time up to the end of the RUL*. Hence assessing the value of using the RUL is of prime importance and gives the decision-maker the true value of cost avoidance when using PHM. Minimizing the amount of remaining useful life thrown away is an example whereby the knowledge about the time of the failure (or time to the failure) allows the decision maker to avoid unscheduled maintenance (where the system is run to failure) and scheduled maintenance (where useful life may be thrown away by changing or removing a part when it still has remaining useful life).

After a prognostic indication, the decision-maker is faced with several actions that can be taken to manage the health of the system. Examples of the actions that can be taken are fault accommodation, changing loads, and tactical control. More formally, in real options' terminology, the decision maker has the right but not the obligation to perform maintenance at a particular point in time [3]. Real Options Analysis (ROA) is used to value or to put a monetary equivalent to the maintenance options arising from the implementation of PHM. The quantifications of the options will eventually lead to means of choosing the best management decisions for the system given some requirements.

## III. Real Options to Manage Flexibility

In this section, options are defined formally along with the characteristics that make up a real options problem to prove the applicability of ROA to the PHM problem. The different valuation methods are discussed along with the choice of appropriate methods for engineering problems. A mapping from real options, to PHM options is suggested to define the key variables, and a solution framework is presented.

### A. Real Options

Options are a way to define the basic element of flexibility. The key property of an option is the asymmetry of the payoff; option holders can avoid downside risks and limit the loss to the price of getting the option, while they can take advantage of the upside risks [14]. PHM installed on a system enables condition-based maintenance where the option holder can perform maintenance contingent on the condition of the asset. If the option is not exercised, the option can expire without being used and unscheduled maintenance has to be performed. In the latter case, the option-holder would have invested in PHM but did not use it, hence the asymmetry of the payoff.

The pre-determined price of an option, is the price of taking an action, and is different from the cost of acquiring the options. The predetermined price for the purpose of this work is the cost of performing a condition-based maintenance action, as opposed to the cost of acquiring the option, which is the cost of acquiring PHM [15].

The following discussion addresses the characteristics that make up a real options problem. The terms options and real options will be used interchangeably from this point onward. The components that make up real options problems are the following [3] and [16]: management flexibility, uncertainties, time and resource restrictions on making and implementing a decision, cost of acquiring (and sustaining) flexibility.

Management flexibility has been discussed at the beginning of this section. However, it is worthwhile mentioning the concept of real options "in" projects that are created by changing the actual design of the technical system: adding PHM to the original system. Real options "in" projects provide a way to define the basic element of flexibility; given a prediction of the remaining useful life, multiple options regarding maintenance arise: maintain now, or maintain later. The other class of options is "on" projects and is common in the literature for investments under uncertainty for projects treating technology as a black box [14], which are not applicable to PHM options because they are financial options taken on technical things. Examples of such options are waiting to invest in an oil field where the key uncertainties are in the price of oil.

Risks and uncertainties (market and private) are part of any engineering problem. At the simplest level, an anomaly detected by a PHM system or algorithm is accompanied with uncertainty. However, we note that risks and uncertainties may be resolved with time (logistics, parts management, etc.), which makes real options an attractive tool for assessing the return from a PHM system or algorithm and its effect on the overall management of the system [17] and [18].

When an anomaly is detected, the time horizon in which the user is allowed to perform action is the 'life' of the option. Maintenance options can be exercised at any point between the anomaly detection until the end of life if no action is taken.

Real options analysis has also been used in engineering technology applications such as RFID [19] and [20]. Past research has focused on cost benefit ratios, discounted cash flows, or net present values to support the decision. Motivation for using ROA in engineering decision making focuses on its ability to account for the uncertainties and the flexibility in the management/investment. Real options have also been used for maintenance applications. For example, work has been done includes the comparison of different maintenance strategies and their effects on the total costs for the maintenance and management of an existing bridge for thirty years [21]. RO have also been applied in the maintenance, repair, and overhaul (MRO) industry [22], the authors compare present value (PV) and RO. The PV analysis resulted in a no-go decision; however using the real options framework justified an investment. Jin et al. [23] used an option-based cost model for scheduling joint production and preventive maintenance for a manufacturing industry when demand is uncertain. The model in [23] provides recommendations for maintenance decision in the environment of uncertain demand.

### B. *Valuation Methods*

Valuating flexibility with models borrowed from financial options is the most commonly used approach in the literature. Models include the Black-Scholes formula, and binomial lattices. Among the numerous assumptions that these methods make, an important one that leads this work to move away from them is the presence of a market security that can used to hedge the risk. When the problem is dominated with market risk (such as the valuation of an oil company's decision to acquire land and drill for oil, with oil price being the only uncertainty considered) the methods used for financial option analysis can be accurate. For projects dominated with technical risk, project management methods such as decision trees represent the value of the flexibility better [24]. For projects including both market and technical risks, a combination of methods from the financial realm and decision sciences represent the value of the project better [25] and [24]. Stochastic dynamic programming has also been sued to deal with flexibility in projects involving technical risks.

Besides the types of risks in the problem, path dependence is a strong influential factor for the choice of method to value flexibility in engineering projects. Engineering projects are typical path dependent in that the value of the project depends on the actions taken by project managers that will change the value of the project. This is not problematic in financial options or projects where there's an asset that can be traded because of the assumption is that the value of the project follows a predetermined random process (Brownian motion, Ito process, and others). Fig. 3 is a schematic representing the two most important factors influencing the choice of method, and the different analysis methods between them.

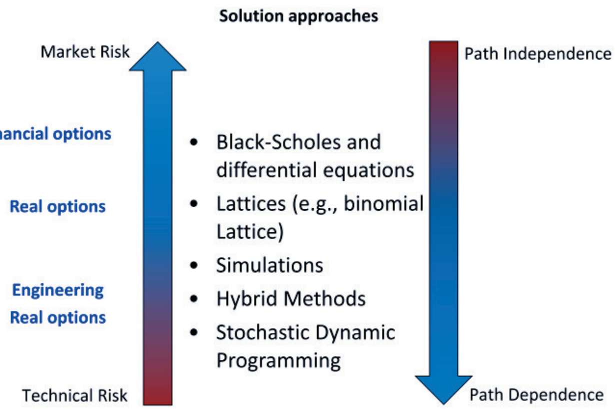


Figure 3- Methods for valuating options

This work will adopt hybrid methods to demonstrate simple options. We note that every option for any application needs to be defined individually as parameters are not the same across applications.

### C. *Mapping From Real To Maintenance Options*

A mapping from financial options to their real option counterpart is proposed in the literature [26]. The extension to their maintenance options is proposed in this work. Table 1 shows the proposed mapping between financial, real, and maintenance options.

TABLE 1- MAPPING OF OPTIONS

| Financial Options (FO) | Real Options (RO) | Maintenance Options |
|---|---|---|
| **Stock** | Asset/Project | System (Asset/Project) |
| **Price of underlying asset: stock price** | "Value" of underlying uncertainties | "Value" of underlying uncertainties |
| **Premium to buy the option** | Premium to buy the option | Sunk cost to implement and sustain PHM |
| **Exercise price** | Cost to carry out the real option | Cost to perform maintenance action |
| **Time to maturity or expiration** | Time by which the real option has to be carried out | Prognostic distance |
| **Dividend payments** | Revenues that are not re-invested in the project | Cost avoidance from optimal maintenance planning |

### D. *Option Exploration and Solution Method*

A number of the benefits or cost-avoidance opportunities can potentially be derived from the knowledge of when the system will fail. Hence assessing the value of waiting represents a new means for monetizing the true value of having PHM on a system. The value of waiting (and related options such as abandoning) are the key to applying RO theory to the PHM problem. Other options such as changing the load are important but not considered in this paper.

When a system is in operation and a prognostic indication is obtained, the decision maker is faced with multiple options. The selection of the best option given a set of requirements is the optimization at the system level. Fig. 4 illustrates the framework.

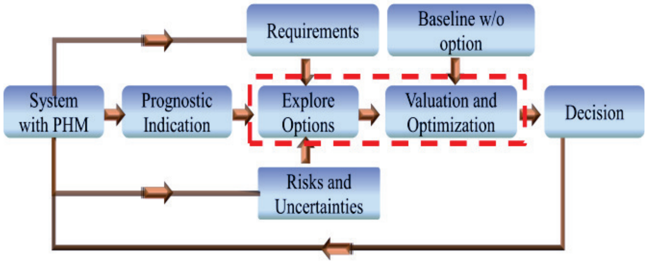


Figure 4- Framework for optimization at the system level

Hybrid methods are appropriate for the valuation of maintenance options. A solution approach encompassing simulations and decision trees can be seen in the flowchart in Fig. 5.

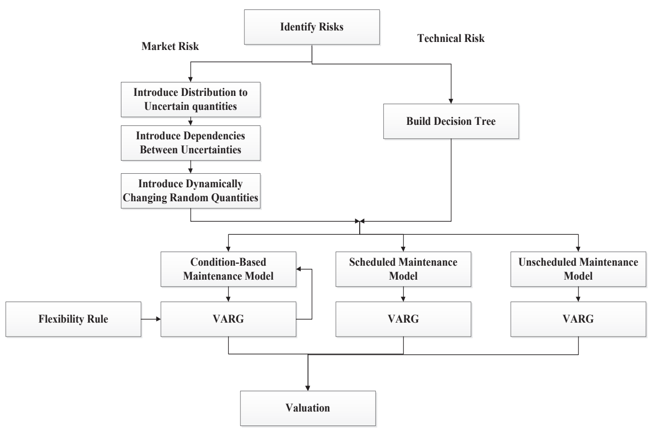


Figure 5- Hybrid solution approach

Initially the maintenance policies are each analyzed individually. Risks are then identified and classified as market or private. Simulations with associated analysis are used for the market risks, and decision trees are used for the private risks. The flexibility rule is influenced by the requirements and the options arising to the decision maker. The Value-at-Risk-and-Gain (VARG) diagram is a convenient way to display the distribution of possible results. It graphs the cumulative value associated with any possible policy. It builds upon the Value-at-Risk (VAR) concept that identifies the risk of the losses they might incur.

## IV. Potential Applications

The use of the proposed framework to the PHM problem is envisioned to be promising for a number of applications. This section discusses two examples for applications where the ROA is believed to be suitable to value flexibility. The first example shows the option to wait in avionics systems, and the second example uses a stochastic dynamic approach to optimize for the turbines to be maintained in a wind farm.

### *A.* Avionics Systems

Assuming an aircraft flying between two cities and a prognostic indication gives a remaining useful life that is enough for a certain number of flights. The decision-maker is faced with several options: the mission can be altered (such as flying to a different destination), depending on the failure mechanism the aircraft may be operated at a slower speed to reduce the operational load, preparations for performing maintenance after the plane lands can be made (call ahead for spares), or the system that had the prognostic indication could be allowed to fail if it is not safety critical.

The example in this section illustrates a waiting option. Data for this example was obtained from [8]. The valuation of the option to wait by Monte Carlo simulation [26] is shown. The underlying assumptions in this example are path independence and the value of the system follows a Brownian motion. It is noted that these assumptions do not hold for maintenance problems but are used here only for illustration purposes.

Table 2 shows the model parameters that will be used for the valuation with:

$$S_t = S_{t-1} + S_{t-1}\left(r * \delta t + \sigma\varepsilon * \sqrt{\delta t}\right) \quad (1)$$

where $S_t$ and $S_{t-1}$ are the underlying asset/mission values at time *t* and *t-1* respectively. σ is the volatility of the underlying asset value. Volatility is a measure of the total value of the underlying asset over its lifetime. It signifies the uncertainty associated with the cash flows [3].

TABLE 2- MODEL PARAMETERS

| Simulation inputs | Symbol | Value |
|---|---|---|
| Current value of the system with PHM capability | $S_0$ | $26,483 |
| Volatility: accounts for risks and uncertainties | $\sigma$ | 0.27 |
| The cost of performing maintenance | $X$ | 2000 |
| The Remaining Useful Life (RUL) predicted by the PHM system | $T$ | 100 |
| Risk free rate (cost of money) | $r$ | 0.07 |
| Time increments | $\delta$ | 1 |
| Epsilon: random variable with standard normal distribution | $\varepsilon$ | |

A discrete event simulator from [8] was used to estimate the volatility. We note that the uncertainties are lumped together in this model; Copeland and Antikarov propose methods to valuate the options with different uncertainties as well. Using the discrete event simulation, the volatility based on uncertain cash flows is estimated to be 27%. The volatility can be visualized in the cone of uncertainty in Fig. 6.

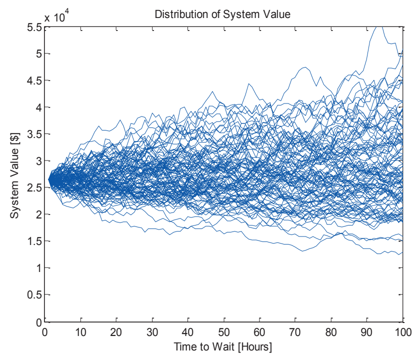


Figure 6- Cone of Uncertainty

The cone of uncertainty visualizes the paths that the value of the asset can take given the uncertainty in the system. The lower and upper paths indicate the boundaries. At time 0, the uncertainty is 0, and increases with time as uncertainty increases. Assuming a prognostic indication in an aircraft system indicates a RUL of 100 hours (enough for 48 flights). The histograms in Fig. 7 show the system value for different waiting times (0, 10, 50, and 100 hours). At time 0, the uncertainty is 0, and the value of the asset is deterministic. As we wait more to maintain the asset, uncertainty will increase and the chance of higher asset value also increase. This is shown by a wider distribution in Fig. 7.

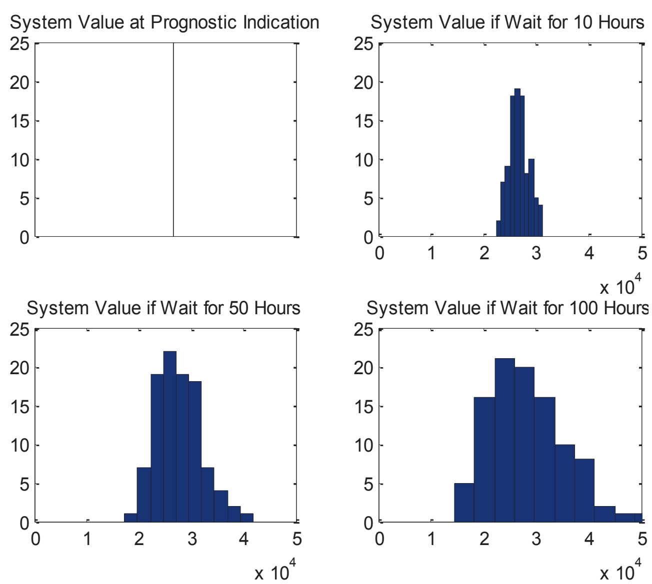


Figure 7- System value for different waiting times

Comparing the mission value with and without CBM will lead to the value of waiting. This will indicate the value added by PHM.

## B. *Maintenance forWind Farms*

The maintenance of wind farms involves the logistics associated with assets needed to perform maintenance and can be costly. If the wind turbines are off shore, for example, sending the maintenance vessel to the wind turbines is an expensive proposition and knowing which of the turbines need to be addressed when the maintenance vessel is on site is important – it may be significantly less expensive to throw away RUL in some wind turbines than to risk having them non-operational or having to make special trips to the wind farm for maintenance. Furthermore, the maintenance and operation (M&O) for wind energy can be as high as 20% of the total life cycle cost of the turbine. Hence optimization of maintenance for these systems provides significant opportunity for cost reduction. A number of authors have attempted to quantify the benefits of using condition monitoring for wind farms such as [27] and [28]. We use the data from [28] to demonstrate the value of PHM which provides options and we use the simulation part of the proposed framework to show the distribution of the net present value (NPV) for implementing CBM. The readers are referred to the paper in [28] for the details of the NPV calculation of implementing CBM. In this paper we include a Weibull distribution for the annual cost reservation with scale parameter 2, and shape 38914. This will result in a distribution of NPV as opposed to a discrete value (272,126 which was obtained in [28]) as see in Fig. 8

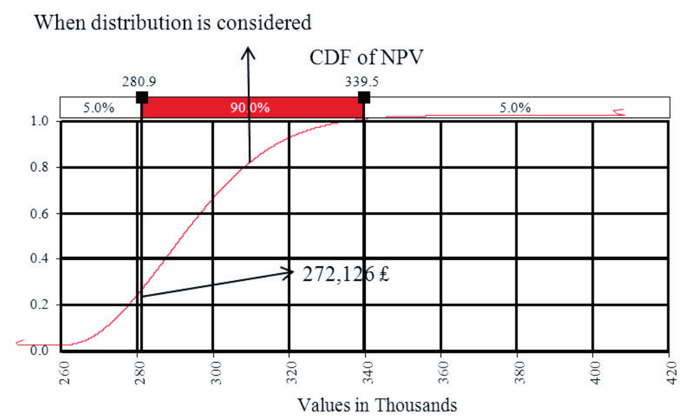


Figure 8- Distribution of NPV

The purpose of this example is to illustrate that accounting for uncertainties is essential and shows the value of PHM in terms of distribution. The simulation can be evaluated whenever a prognostic indication is obtained, and the uncertainties can be included in the model. This will provide the decision maker with means to benefit from the upside of having PHM, and take appropriate actions when the uncertainties are not in favor of the project.

## V. Conclusions and Future Work

This paper is a first attempt to addresses the economic aspect of PHM after a prognostic indication. It provides the decision-maker with a tool to optimize maintenance decisions, and a method to quantify the cost-avoidance obtained from PHM. We introduce for the first time the concept of flexibility induced by PHM, and demonstrate how options can be used for the health management of the system. Real Options Analysis was introduced along with the different valuation methods and arguments supporting the methods appropriate for the PHM problem. A mapping from real options to what we define as PHM option is introduced and will serve as a reference to understand and valuate new options arising from PHM. This method provides means to assess the value of PHM from a investment standpoint. It is a new method to assess the return from PHM after prognostic indication. Finally, this method can provide means to study the investment needed in PHM in order to satisfy a particular availability requirement. Other questions that can we plan to address with the proposed framework would be the extra investment in PHM needed to meet a certain availability, the investment a decision-maker should make for PHM to meet the requirements, the value of waiting to perform maintenance for a fleet of systems.

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