# Incorporation of Outcome-Based Contract Requirements in a Real Options Approach for Predictive Maintenance Planning

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# Motivation

- Outcome-based contracts are growing in popularity for both governmental and non-governmental acquisitions
  - 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
- Predictive Maintenance planning seeks to predict and optimize when predictive maintenance for a system is performed
  - Condition-monitoring technologies such as Condition-Based Maintenance (CBM) and Prognostics and Health Management (PHM) provide Remaining Useful Life (RUL) estimates
  - Predictive maintenance = maintenance performed as a result of an RUL (as opposed to preventative and corrective)
- The challenge is how to use the predicted RULs (with their uncertainties) and the requirements imposed by the outcome-based contracts to optimally plan predictive maintenance

# Where We are Going …

This research addresses the incorporation of outcome-based contract requirements within a real options approach used to optimize predictive maintenance planning

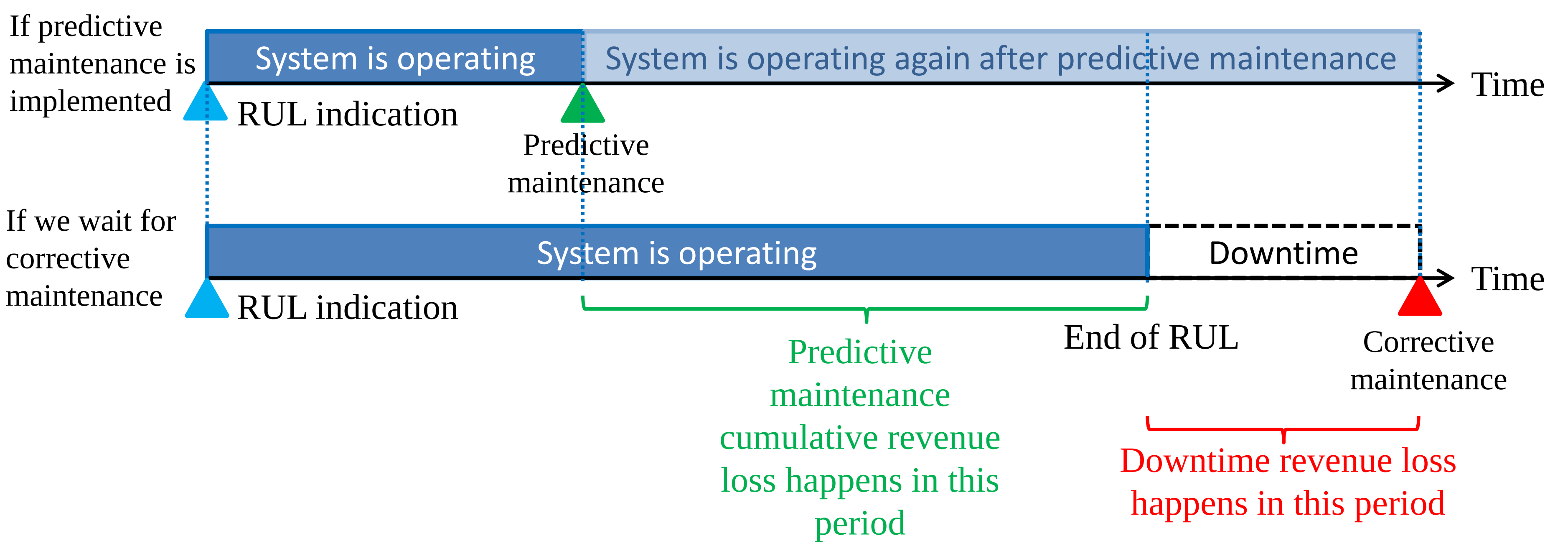
1) A simulation-based real options analysis (ROA) approach is used to determine the optimum predictive maintenance opportunity for a single revenue-earning system
2) Address a population of revenue-earning systems managed via an outcome-based contract
3) The ROA approach is extended to non-revenue earning systems

# A Real Options View of Predictive Maintenance – Revenue-Earning System

- Real Options: The flexibility to alter the course of action in a real assets decision, depending on future developments.
  - The buyer of the (call) option gains the right, but not the obligation, to engage in the transaction at the future date
- Predictive maintenance opportunities triggered by RUL predictions can be treated as Real Options
  - Buying the option = paying to add PHM into a system
  - Exercising the option = performing predictive maintenance prior to failure
  - Exercise price = predictive maintenance cost
  - Value returned by exercising the option = cumulative revenue loss (negative) + avoided corrective maintenance cost (positive)
  - Letting the option expire = doing nothing and running the system to failure then performing corrective maintenance
- Revenue-earning system = a population of systems for which the unavailability penalty is lost revenue, e.g., airline, wind farm, rental car fleet, etc.

# Predictive Maintenance Value Simulation for a Single Revenue-Earning System

- Cumulative revenue loss
  - The difference between the cumulative revenue from the RUL indication to the predictive maintenance event, and from the RUL indication to the end of the RUL
- Avoided corrective maintenance cost includes:
  - Avoided corrective maintenance parts, service and labor cost
  - Avoided revenue loss associated with corrective maintenance downtime
  - Avoided under-delivery penalty due to corrective maintenance (if any)



## If the system is fixed and operates again after the predictive maintenance event why is the predictive maintenance revenue loss included in the option value?

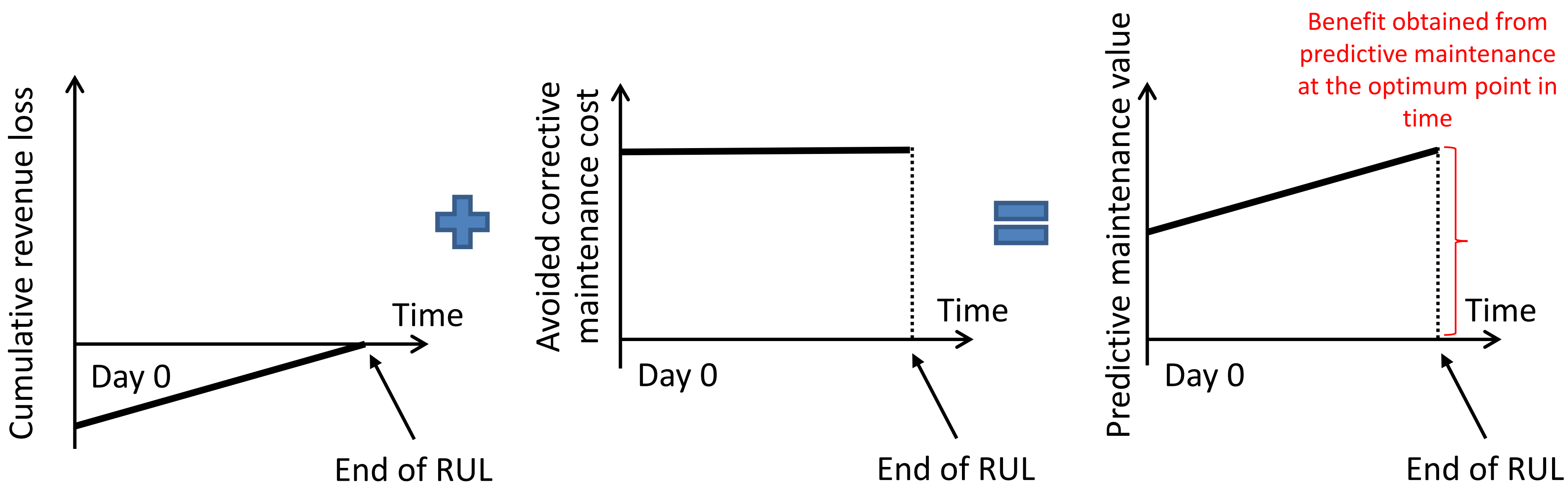
THIS IS HOW THE WHOLE LIFE-CYCLE VALUE OF THE MAINTENANCE EVENT IS ACCOUNTED FOR

This reflects the value of this maintenance action in the whole life-cycle of the system. In other words the RUL thrown away may not cost you money now, but it costs you money later in the life-cycle in the form of more maintenance actions and more spares.

- Note, if you only do corrective maintenance (break-fix) it represents the minimum number of maintenance actions and minimum number of spares for the system (assuming no collateral damage).
- The model attempts to make the best use of each RUL in the life-cycle to maximize the life-cycle net revenue by balancing between the less frequent but more expensive corrective maintenance actions and the more frequent but less expensive predictive maintenance actions.
- After the predictive maintenance we replace a new system, and start a new cycle to consume the lifetime of the new system until its RUL indication. So in this sense we are “tracking” the system, and maximizing the net revenue of the system during each cycle.

# Predictive Maintenance Value Simulation for a Single Revenue-Earning System

- Predictive Maintenance Value = Cumulative revenue loss + avoided corrective maintenance cost

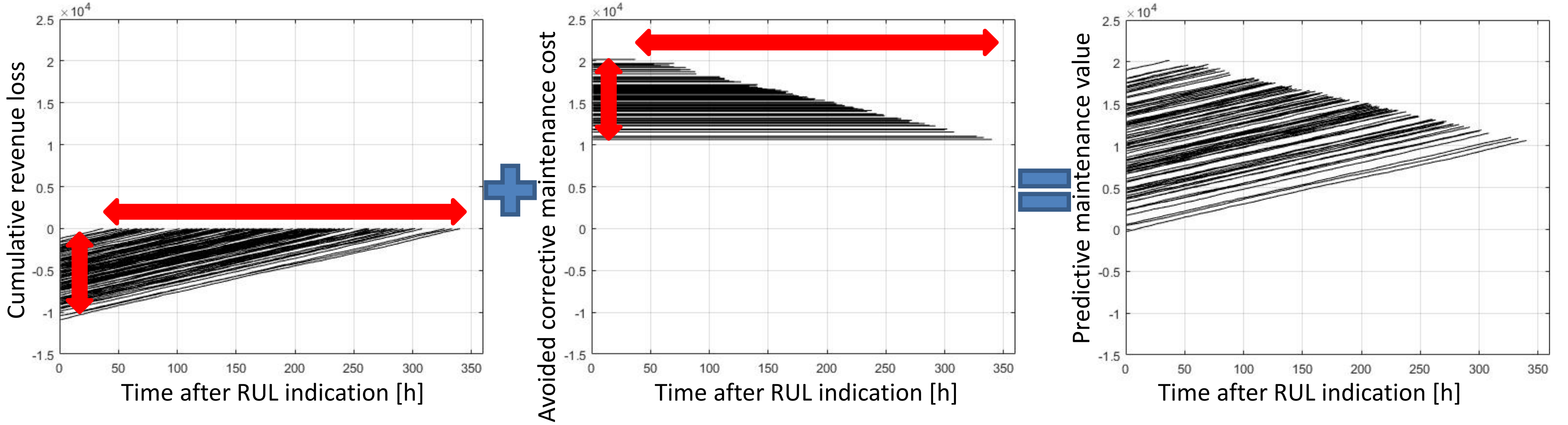


# Path Generation (Uncertainties)

Path = starting at the RUL indication (Day 0), it represents one possible way that the future could occur

- The cumulative revenue loss path represents the possible revenue due to uncertainties in the market and required resources
- The avoided corrective maintenance cost path represents how the RUL is used up and varies due to uncertainties in the predicted RUL
- Each path is a single member of a population of paths representing a statistically significant set of possible future system states

# Predictive Maintenance Value Simulation for a Single System (continued)

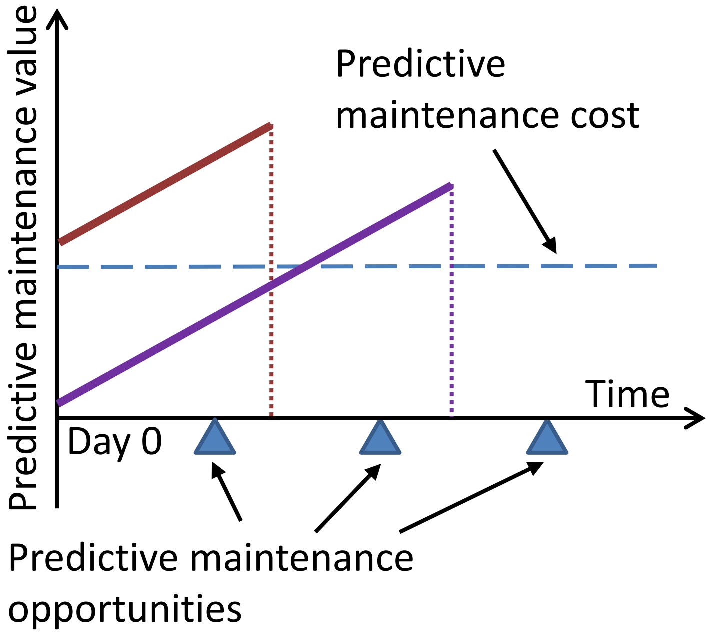


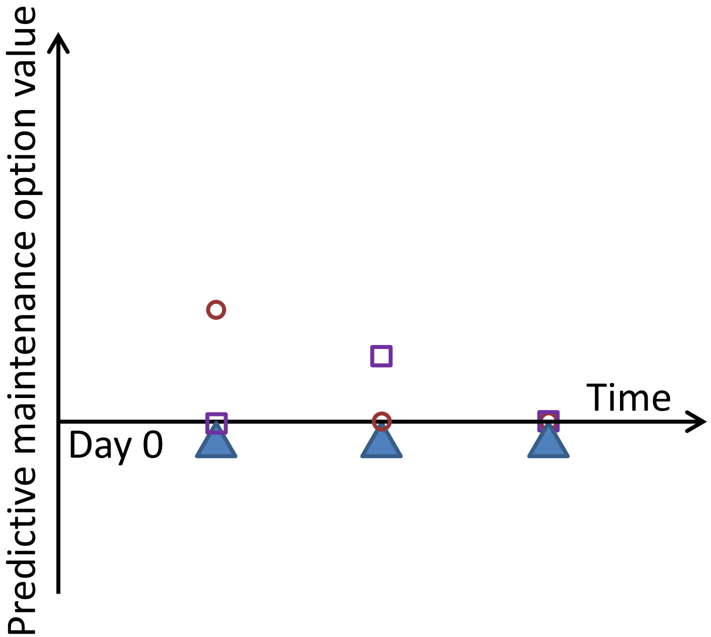

- Due to the uncertainties in RUL predictions each path terminates at a different point
  - The point is the last predictive maintenance opportunity before the TTF (time to failure)
  - The shorter the TTF, the sooner the cumulative revenue loss and the avoided corrective maintenance cost paths terminate
- Due to the uncertainties in RUL predictions each path starts at a different point
  - The shorter the TTF, the higher the cumulative revenue loss path starts, because the revenue loss due to predictive maintenance is lower
  - The shorter the TTF, the higher the avoided corrective maintenance cost path starts, because the downtime revenue loss is higher

*So how do we schedule the predictive maintenance based on this set of paths?*

# Predictive Maintenance Option Valuation for a Single System (continued)

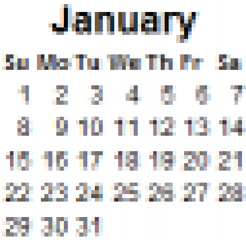
- We assume that predictive maintenance can only be performed on specific dates
- On each date, the decision-maker has flexibility to determine whether to implement the predictive maintenance (exercise the option) or not (let the option expire)
- This makes the option a sequence of "European" style options that can only be exercised at specific points in time in the future
- Real Option Analysis (ROA) is performed to valuate the option



# Example Revenue-Earning System

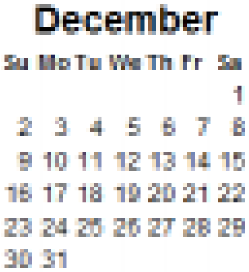
Predicted Remaining Useful Life (RUL)




Options:
- Switch to a redundant subsystem (if any)
- Slow down
- Shut down
- Do nothing

Predictive Maintenance Opportunity

Options:
- Maintain at earliest opportunity
- Wait until closer to the end of the RUL to maintain
- Run to failure for corrective maintenance




If I could determine the <u>value</u> of each of the options, I would have a basis upon which to make a decision about what action to take in response to the RUL prediction

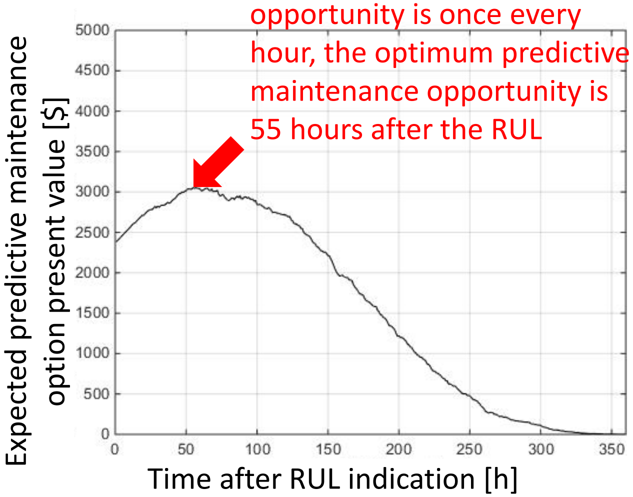
# Predictive Maintenance Option Valuation for a Single Turbine (continued)

- On each predictive maintenance opportunity date, the European ROA approach is implemented on all paths
- The results are averaged to get the expected predictive maintenance option value 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

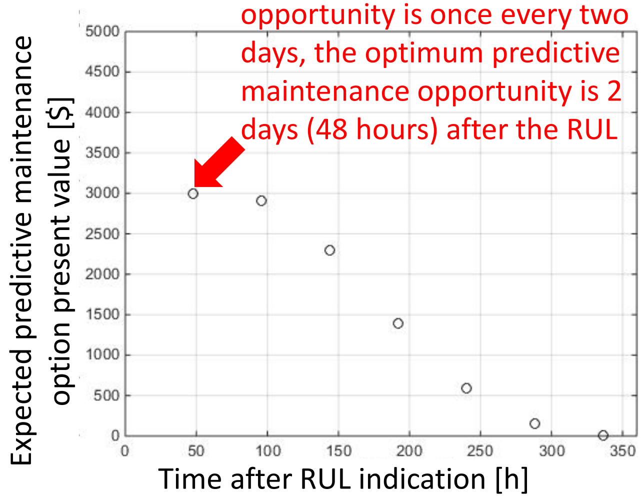
At the optimum date:

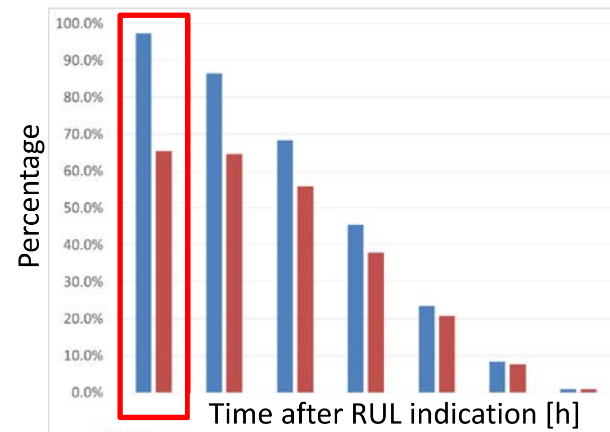
- The predictive maintenance will be implemented on 65.3% of the paths
- 32.0% of the paths choose not to implement predictive maintenance since the predictive maintenance value is lower than the predictive maintenance cost
- In 2.7% of the paths the turbine failed prior to the predictive maintenance

If predictive maintenance opportunity is once every hour, the optimum predictive maintenance opportunity is 55 hours after the RUL




If predictive maintenance opportunity is once every two days, the optimum predictive maintenance opportunity is 2 days (48 hours) after the RUL




Blue: percentage of the paths with the turbine still operating

Red: percentage of the paths choosing to implement predictive maintenance

*The ROA approach is not aiming to totally avoid corrective maintenance, but rather to maximize the predictive maintenance option value*

# Extension to a Population of Systems with an Outcome-Based Contract (a Wind Farm)

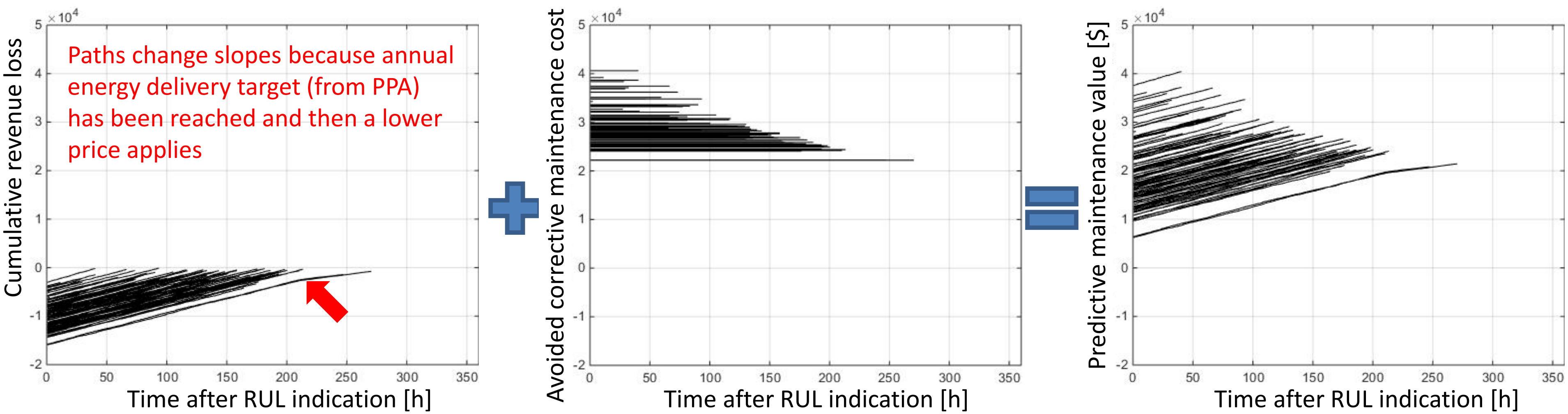
- A wind farm may consist of hundreds of individual wind turbines
- Wind farms are typically managed via outcome-based contracts called PPAs - Power Purchase Agreements
- Maintenance will be performed on multiple turbines (and multiple turbine subsystems) on each maintenance visit to the farm because,
  - Expensive resources are required (e.g., cranes, helicopters, vessels)
  - Maintenance windows may be limited due to harsh environments

# Modeling the Outcome-Based Contract

- The outcome-based contract (a PPA in this case) will influence the combined predictive maintenance value paths
  - Cumulative revenue loss is influenced by:
    - Contract energy price
    - Over-delivery energy price
    - Wind farm annual energy delivery target
    - Wind farm cumulative energy delivery from the beginning of the year to the RUL indication
  - Avoided corrective maintenance cost due to predictive maintenance is influenced by:
    - Contract energy price
    - Over-delivery energy price
    - Compensation energy price
    - Wind farm annual energy delivery target
    - Wind farm cumulative energy delivery from the beginning of the year to the RUL indication

# Predictive Maintenance Value Simulation for a Wind Farm

- Assume a 5-turbine-farm managed via a PPA, Turbines 1 & 2 indicate RULs on Day 0, Turbine 3 operates normally, Turbines 4 & 5 are down
- Predictive maintenance revenue lost, cost avoidance and predictive maintenance value paths for Turbines 1 & 2:



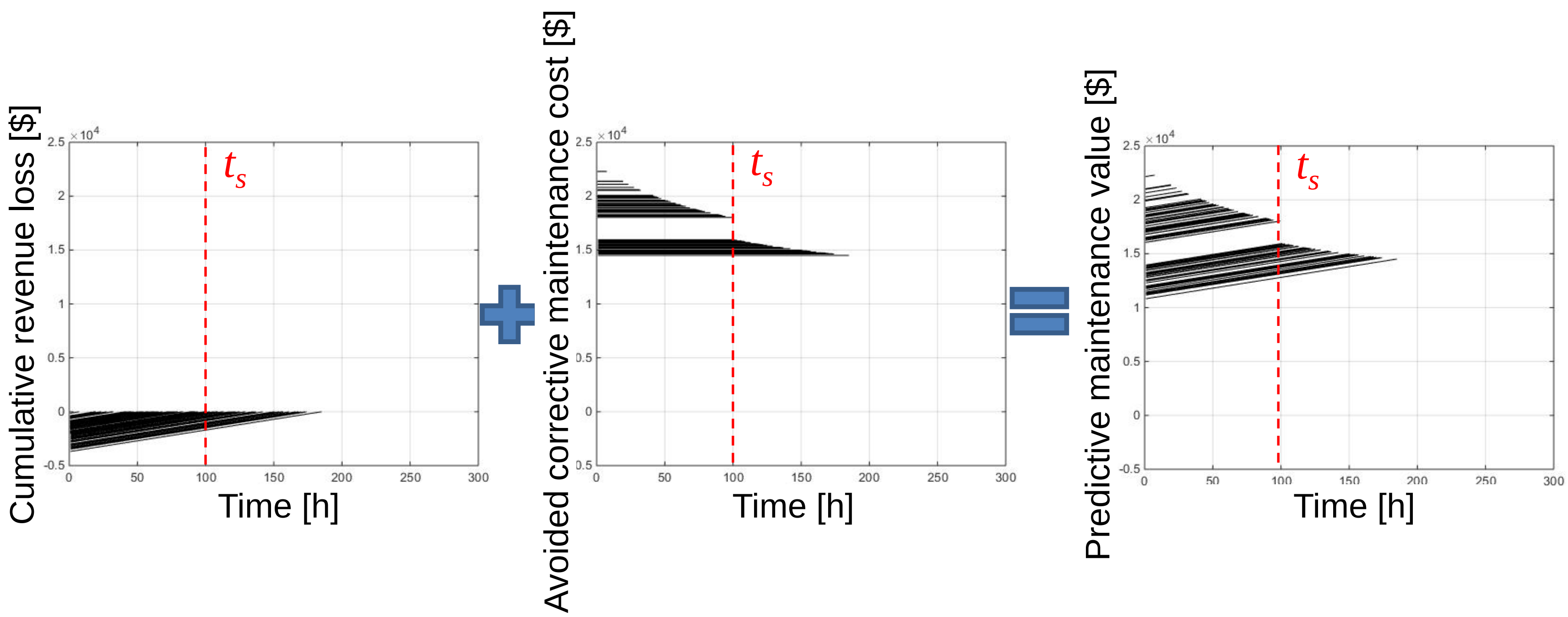
# Non-Revenue Earning Systems

- Assume a single system (e.g., an aircraft engine) with PHM embedded
  - 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), in which availability is the contracted 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 customer requires a minimum availability. If the actual achieved availability fails to meet the requirement the contractor is penalized.
  - The contractor is responsible for all the maintenance activities.
  - Predictive maintenance is assumed to have a lower cost and shorter downtime than a corrective maintenance.

# Non-Revenue Earning Systems – Inventory Management

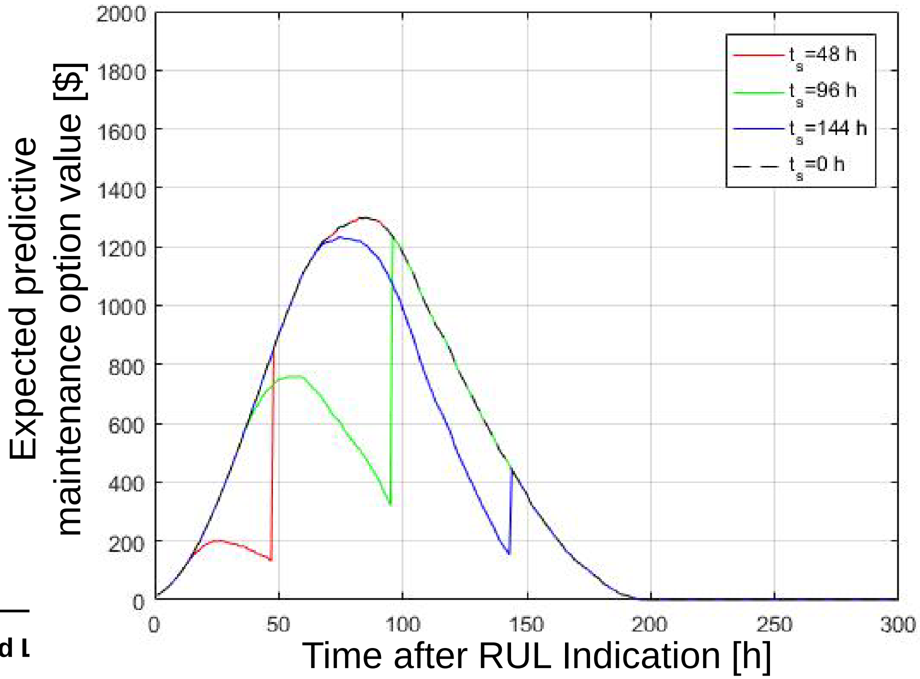
- The decision to act on an RUL indication will be influenced by the inventory of spares (for the system) that are available
- The goal of this model is "when-to-act" NOT "how many spare parts to order". This assumption allows the model to be extended to the case of multiple systems using a single shared inventory (e.g., a fleet of aircraft all drawing engines from the same inventory)
- Model:
  - Upon RUL indication, the spare part needed to fix the system is not available and it takes some time $t_s$ for it to become available
  - If the event is corrective maintenance, and it happens before $t_s$, a penalty on the contractor will occur (e.g., to expedite the spare part order), which will be reflected in the avoided corrective maintenance cost
  - If the event is predictive maintenance, and it happens before $t_s$, a penalty will also occur and be reflected in the predictive maintenance cost (the exercise price of the option)
  - In practice, $t_s$ comes from a probability distribution that models the arrival of the spare part

- The cumulative revenue loss, the avoided corrective maintenance cost and the predictive maintenance value paths can be simulated
- The avoided corrective maintenance cost in the middle plot and the predictive maintenance value paths in the right plot separate into two groups where the penalty for implementing corrective maintenance before $t_s$ occurs to the upper group of paths and not in the lower.



# Non-Revenue Earning Systems – Optimum Predictive Maintenance Date

- $t_s$ =0 represents the base case in which the spare is available at the RUL indication
- When $t_s$ changes, the shape of the expected option value curve will change, and the optimum predictive maintenance date (the peak of each curve) may also change
  - Before $t_s$ each curve is lower compared with the base case, because fewer paths will choose predictive maintenance, since the exercise price is higher due to the spare penalty
  - The earlier the $t_s$, the larger the difference from the base case, since more paths will not choose predictive maintenance due to the high exercise price before $t_s$
  - After $t_s$ the curve will coincide with the base case (the jump up at its $t_s$)



# Summary

- Our objective 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
  - The optimum action to take 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-revenue earning 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