IPOP, an industrial assets management tool to support Integrated Life Cycle Management

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Abstract: IPOP, for Investments Portfolio Optimal Planning, is a tool dedicated to industrial assets management. It features different quantification modules to support decision making regarding maintenance of major components of a nuclear power plant and spare part purchases. This paper describes IPOP and its link with EPRI Integrated Life Cycle Management (ILCM) software suite. The integrated use of the tool is illustrated with a test-case.

Keywords: Asset Management, Optimization, Simulation, Maintenance, Life Cycle Management

1. INTRODUCTION

The purpose of this paper is to describe IPOP (Investments Portfolio Optimal Planning) software, developed by EDF, dedicated to optimize investments planning for major nuclear components to support decisions for long term operation. After a description of the software, the paper will focus on its integration into the ILCM (Integrated Life Cycle Management) tool developed by EPRI. As a matter of fact, IPOP by itself doesn't assess the likelihood of failures which is a major input of any engineering asset management study; this is the reason why IPOP must be a part of a global method that includes a failure curve database such as the one implemented in ILCM. The use of IPOP in the ILCM method will be illustrated by a real case application of the tool describing the different steps of the method and highlighting the importance of taking into account risk indicators in the decision making process.

2. INVESTMENTS PORTFOLIO OPTIMAL PLANNING (IPOP)

2.1. Software description

EDF R&D has been working for over a decade on different industrial assets management issues, in particular for nuclear generation [1]. In order to support decision making for its fleet of nuclear power plants, EDF has developed software, named IPOP for Investments Portfolio Optimal Planning, with three different modules (Mean Value Calculation Program, Optimization Algorithm and the Risk Indicators Calculation Program). This tool allows dealing with several dimensions of studies from a single component to the analysis of all major components over a fleet of plants. IPOP supports decision making for choosing between alternative maintenance strategies, prioritizing investments or comparing broader strategies.

As defined in IPOP a portfolio of investments is made of two types of investments:

- Preventive maintenance tasks: these investments reduce the probability of failures, that is to say the risk frequency.
- Spare parts purchases: these investments reduce the consequences of failures by avoiding long forced outages, that is to say the risk consequence.

IPOP is made of three different modules:

1. Mean valuation module: based on a Piecewise Deterministic Markov Process (PDMP) model, this module enables fast computations of mean indicators to assess the profitability of an investments strategy.
2. Optimization module: this module optimizes the selection of investments and their scheduling based on the mean indicators computed with the previous module, taking into account various constraints. It uses Genetic Algorithms to perform this optimization.
3. Probabilistic valuation module: based on an event model and Monte-Carlo simulation, this module enables the computation of probabilistic indicators to assess the risk exposure of an investments strategy.

Figure 1 presents the articulation between these different modules.

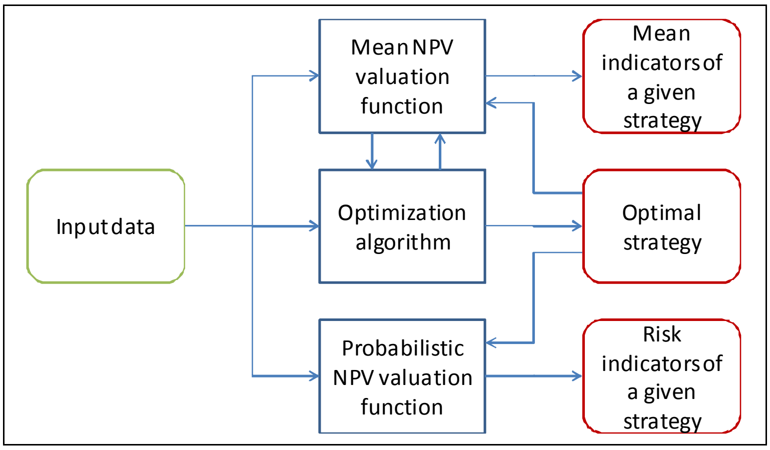

Figure 1 - IPOP architectures

The different mathematical models have already been described in [2] for the Monte-Carlo simulation , as for the optimization with Genetic Algorithms of PDMP models it was fully presented in [3] and [4].

2.2. Investments correlation

The complexity, when optimizing a portfolio of investments, comes from the fact that the investments are correlated and that the optimal date of an investment if it was made by itself may be very different than its optimal date in a global planning. There are three major sources of correlation between investments:

1. Common spare parts: as described in Figure 2, in IPOP, components are structured into families of components using the same technology of spare parts. In such a model, the failure or the replacement of one component on a given plant may have an indirect impact on another component, as it may use a spare part that would also be needed if another component was to fail.

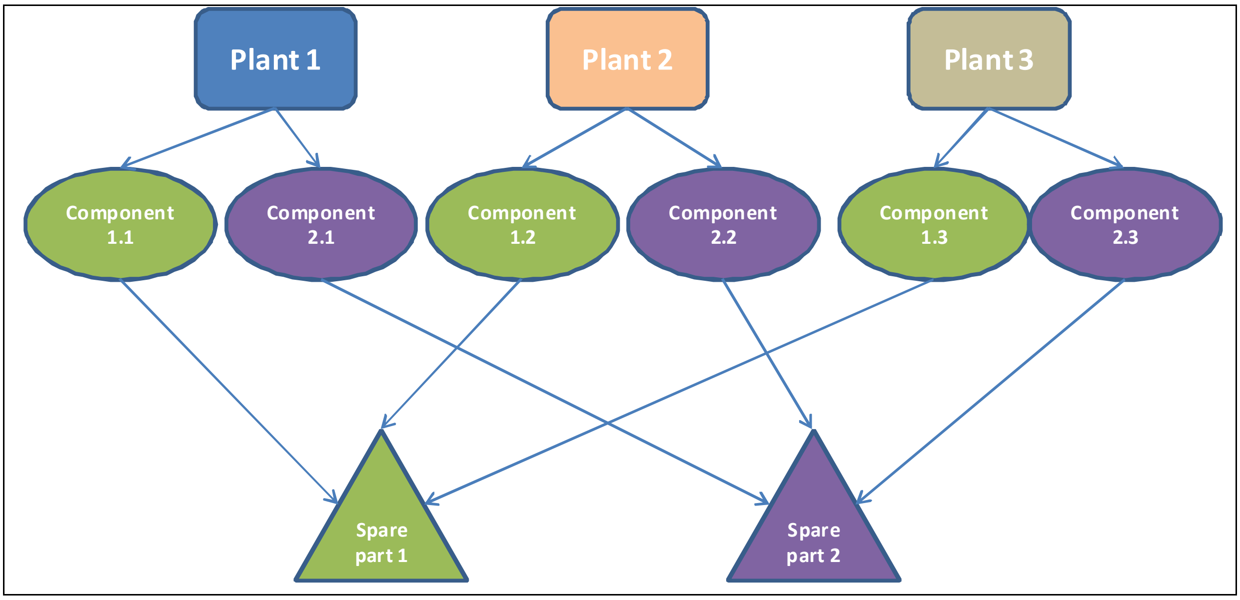

Figure 2 - IPOP elements structure

2. Decommissioning: IPOP does not include an availability model so that it is possible to structure the different components as a dynamic system. All components, as long as they belong to different families of components, are assumed to be independent. The only exception is for failure of components leading to an anticipated decommissioning of the plant (for example non repairable life-limiting components such as the containment structure or the reactor pressure vessel), in this case all other components installed on the same plant will not be able to generate further failures or cash-flows.
3. Constraints: in the optimization process, different types of constraints may be taken into account. Some constraints may be logistical ones such as the industrial capacity of a supplier limiting the number of components that can be replaced each year. Another type of constraints is exogenous decision, such as a regulatory issue for example, making some investments mandatory even though they would not be profitable. At last, a third type of constraints is the one concerning budget limit, whether it is a global or an annual limit. Figure 3 and Figure 4 present an example of an optimal replacements planning for a set of 20 components with and without a budget constraint (budget limit is $11.5M). Adding such a constraint tends to stretch out the investments over a longer time period (e.g. component 11 is replaced at year 7 instead of year 1) making the planning suboptimal in terms of profitability but feasible in terms of costs control.

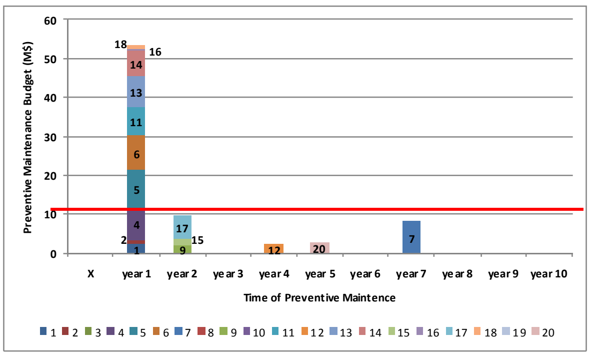

Figure 3 – Example of an optimal planning of the replacements of 20 components without budget limit

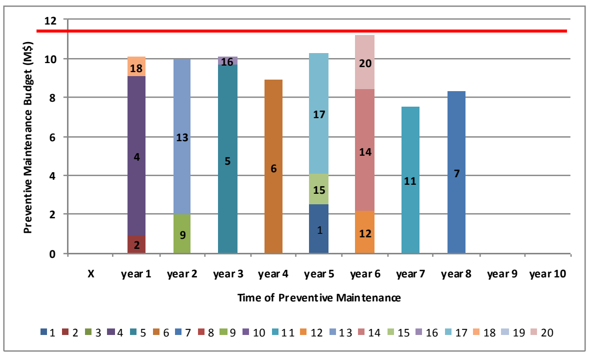

Figure 4 - Example of an optimal planning of the replacements of 20 components with a budget limit

As a consequence, an optimal planning of a portfolio of major investments is not the simple aggregation of individual optimal dates of investment, as it will be shown in the test-case in §4.

3. IPOP FOR INTEGRATED LIFE CYCLE MANAGEMENT (ILCM)

Integrated Life Cycle Management (ILCM) is an EPRI project which started in 2010 with two aims [5]:

- Provide a standard methodology to support effective decision-making for the long-term management of selected station assets.
- Provide technology to give a sound basis for continued operation of the current nuclear plants at high performance levels through 2030 and beyond.

The three actions that are required to achieve these goals are:

1. Development of "Likelihood of Failure" (LoF) Curves.
2. Development of optimum replacement or refurbishment strategy method.
3. Creation of an EPRI Software Tool to integrate the Failure Calculator module and the Optimization module into a single easy-to-use software tool.

EDF IPOP software was chosen to be part of the ILCM tool. The articulation between all different modules is described in Figure 5. IPOP takes for inputs technical and financial data and the results of LoF calculation performed with the database developed by Lucius Pitkin inc. [5].

Several test-cases have been made to test the different tools as well as their coupling. The Beta-version of ILCM has been released in late 2013.

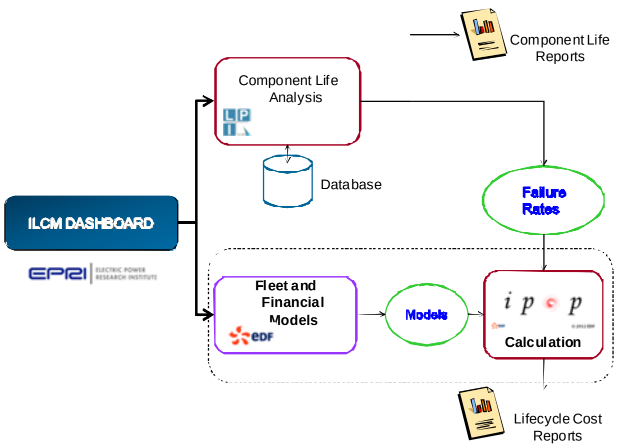

Figure 5 – ILCM global architecture

4. TEST-CASES

Here are presented the IPOP results of one test-case carried out with the complete ILCM software suite. Data used for this example is not real data, as the test was only a demonstrator of the capability of the tools, but it was gathered with system engineers and business manager so that it is realistic and representative of real-world issues.

4.1. Test-case description

This example deals with a family of four components installed on two different plants (two components on each plant). The failure of one component leads to a forced outage (series system). Failure curves of these components have been calculated with the ILCM database (see Figure 6). The results of these calculations show that three of the components have an identical reliability and that the last one presents a higher risk of failure as it had experienced previous failures that have been repaired. At the time of the study, all four components were 10 years old.

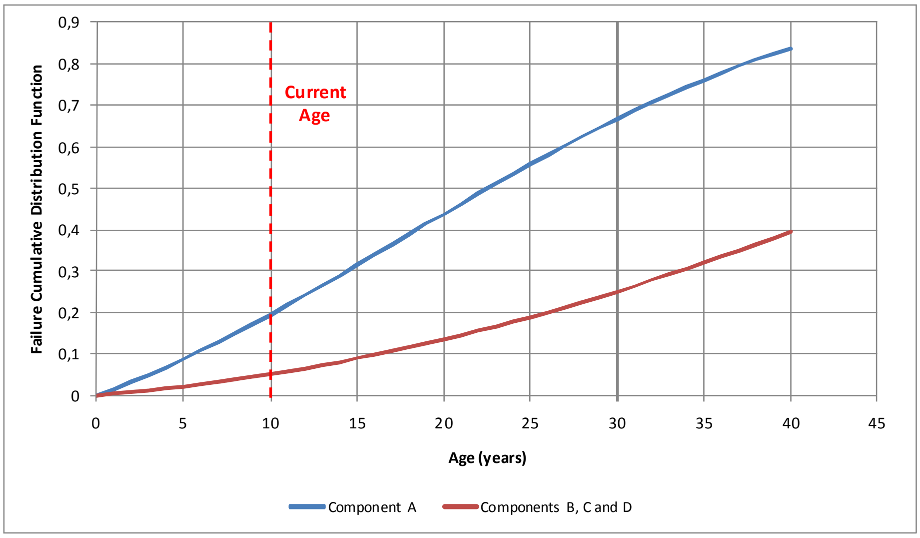

Figure 6 – Components reliability from ILCM failure curve database

As for the other parameters of the test-case, we have:

- Two identical plants with a decommissioning date in 2040
- One day of forced outage is $1M
- The cost of one component is $5M
- The cost for making the replacement (labor, engineering costs…) is $2M
- The time to make a corrective replacement is 20 days
- A preventive replacement may be done within a planned outage
- The supply lead time for a component is 1 year
- Corrective and preventive replacements are assumed to be As Good As New (AGAN), that is to say the reliability of all components after replacement, including component A, is the same as the reliability of components B, C and D aged zero.
- The annual discount rate is 10%
- Study starting date is 2010.

The possible investments that can be made are:

1. Preventive replacement of a component
2. Purchase of a spare-part to avoid long forced outage in case of a failure

4.2. Individual optimal strategies for life-cycle management

If all components were independent it would be possible to test all possible dates for each investment (including not making this investment) and to choose the date giving the lowest Life Cycle Cost (LCC) that is made of the different cash flows induced by the component (failures, preventive replacement, time waiting for a spare part…). Figure 7 presents these LCCs for different dates of replacement: we can see that the best choice would be to make the preventive replacement of the component in 2015 as its LCC would then be minimal at $29.8M.

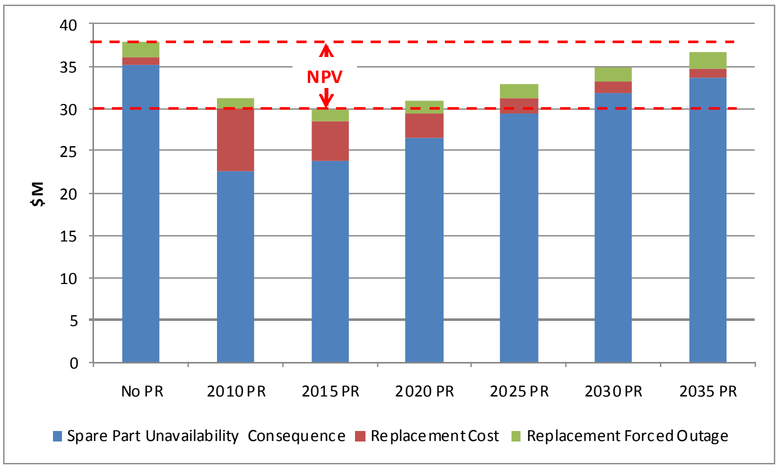

Figure 7 – LCM strategies comparison for component B

The Net Present Value (NPV) of the strategy is the LCC difference between this strategy and the reference one (corresponding to making no preventive replacement at all). In this case the NPV of making a preventive replacement in 2015 is then:

$$NPV(2015) = LCC(\emptyset) - LCC(2015) = 38 - 29.8 = \$8.2M$$

Figure 7 only shows the values for preventive replacement from five years to five years to simplify the graph, but IPOP is actually able to optimize the replacement dates on a year to year base testing, in this case, all 30 possible years. Table 1 presents the optimal strategies taken independently.

	Component A	Component B	Component C	Component D	Spare Part
Optimal Year	2010	2015	2015	2015	2010
Optimal NPV	$80.4M	$8.2M	$8.2M	$8.2M	$197.4M

Table 1 – Individual optimal Life Cycle Management strategies

As component B, C and D are identical, their individual optimal Life Cycle Management (LCM) strategies are the same with a replacement year in 2015 and a NPV of $8.2M. Component A should be replaced as soon as possible (in this case in 2010, the starting date of the study) with a NPV of $80.4M: the difference comes from the fact that this component is less reliable and a replacement will avoid more failures. As for purchasing a spare part, without making any preventive replacement, it should be done as soon as possible with a NPV of $197.4M coming from a decrease in the time to get a spare if needed but not a decrease in the risk to need a spare (action on the consequence of a failure and not on its frequency).

The factor 10 between the optimal NPV of component A and the other ones comes from the significantly higher failure rate for this component, especially in the first years of the study for which the discount rate impact is the lowest. Replacing a component will avoid two kinds of events associated to failures, the first one is the forced outage to wait for a spare part (it will depend on the number of spares, the failures of other components…) and the forced outage to make the replacement (20 days, independently from other components behavior). In order to illustrate the impact of component A reliability, the cumulated cash-flows for the global study were computed if component A was as reliable as the others (with no investments at all). The comparison made in Figure 8 highlights the fact that component A bad reliability increases the global average risk by more than $70M which is coherent with the orders of magnitude of the independent NPVs presented in Table 1.

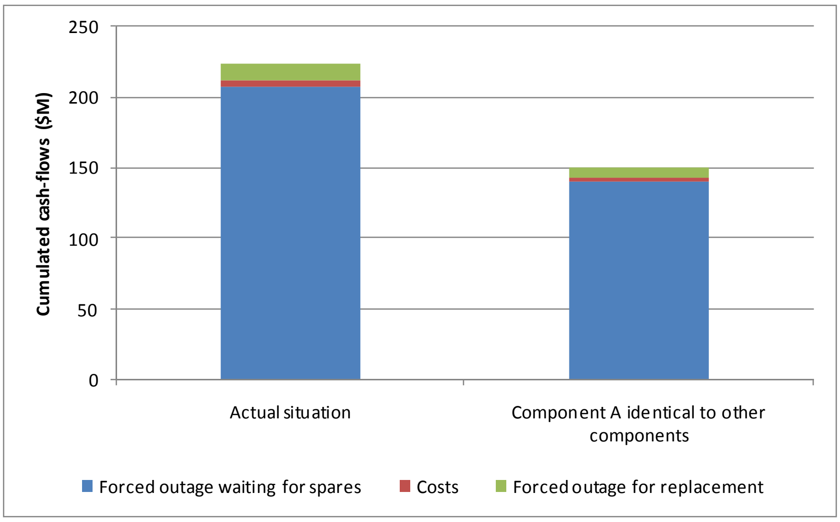

Figure 8 – Component A bad reliability impact on cash-flows

4.3. Global optimal strategy for Integrated Life-Cycle Management

The first thing to do is to evaluate globally the aggregation of individual strategies. On Figure 10, presenting the evolution in time of the cumulated cash flows, we can clearly see the two years of investments with the cost curve (blue) having two stairs in 2010 (spare part purchase and replacement of component A) and 2015 (replacements of components B, C and D). If we compare the two strategies (Figure 9 and Figure 10) we see that the benefit of making these investments is that the mean value of the risk of forced outage is reduced by a factor 30.

The NPV, that is the difference of the cumulated cash-flows generated by the "do-nothing" strategy and the studied one is, in this case, $190.7M. It is logical that the global NPV is smaller than the sum of individual optimal NPVs as some of the risks avoided by a replacement may also be avoided by purchasing a spare part; summing them is then not appropriate as some profits would be counted twice.

$$NPV_{Glob} = 190.7 < NPV_A + NPV_B + NPV_C + NPV_D + NPV_{Spare} = 302.4$$

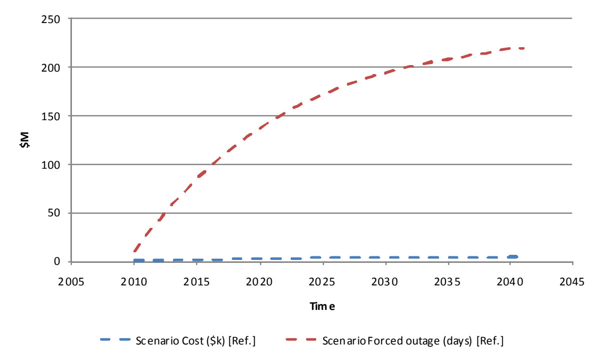

Figure 9 – Cumulated cash-flows for the reference strategy

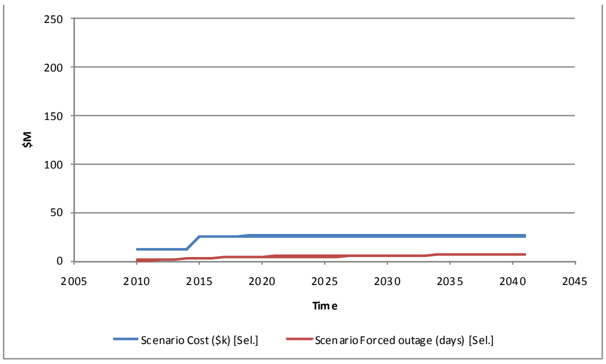

Figure 10 – Cumulated cash-flows for the aggregation of individual best strategies

If the global NPV is different from the sum of individual optimums, it is also likely that the integrated optimal strategy is different from the aggregation of individual ones. As a matter of fact, purchasing a spare part and replacing components are investments that may present overlapping mitigations of the risk. This is the reason why it is important to perform a global optimization of the strategy, which is possible thanks to IPOP optimization module. The Genetic Algorithm implemented in IPOP has no problem finding the best solution among the $30^5=2{,}43.10^7$ possible strategies (which remains a small optimization problem). The comparison between the two strategies is given in Table 2.

	Component A	Component B	Component C	Component D	Spare Part	Global NPV
Integrated Optimal strategy	2013	-	-	-	2010	$199.5M
Aggregation of individual strategies	2010	2015	2015	2015	2010	$190.7M

Table 2 – Comparison of the integrated strategy and the aggregation of individual strategies

The results show that the main priority is to purchase a spare that would be useful to all components in order to control the risk of a one year forced outage after a failure. As in the individual strategies, the purchase of a spare has to be done as soon as possible.
Once the spare part is available, the preventive replacements of the components are not as urgent. Components B, C and D which should be replaced in 2015 if they were studied independently from the rest of the family of components, now do not need to be replaced in the remaining lifetime of the plants.
As for component A, the preventive replacement is still profitable but it should be postponed until 2013. The global NPV is about 5% higher than the NPV of the strategy consisting in aggregating individual best strategies. This calculation highlights the importance of performing an Integrated Life Cycle-Management.

4.4. Risk-informed valuation of ILCM strategies

An important thing to look at when dealing with ILCM strategies is the residual risk associated with a strategy. As a matter of fact, ILCM is dedicated to large assets often characterized by a low probability of failure but large consequences, it is then essential to quantify the risk exposure of a strategy through a probabilistic assessment. This evaluation was performed on the test-case with the IPOP dedicated module. The main risk indicators are presented in Table 3.

	Integrated strategy	Aggregation of individual strategies
Mean NPV	$200.4M	$192.4M
NPV standard deviation	$156.5M	$164.8M
Probability of regret (Prob(NPV<0))	0.027	0.082

Table 3 – Strategies risk assessment

We can see that the difference of mean NPV between the two strategies is very close from the one obtained with the mean valuation module used for the optimization (the small difference comes from the approximations used in the PDMP model), with the integrated optimal strategy having a NPV $8M higher.
The standard-deviation of the integrated strategy is a bit smaller, which could be an indication that the risk dispersion is lower. But more important is the probability of regret, that is to say the probability that the set of investments does not turn out to be profitable with a negative NPV. With the integrated strategy, this probability of regret is the third of the one of the aggregation of individual strategies, decreasing from 8.2% to 2.7%.

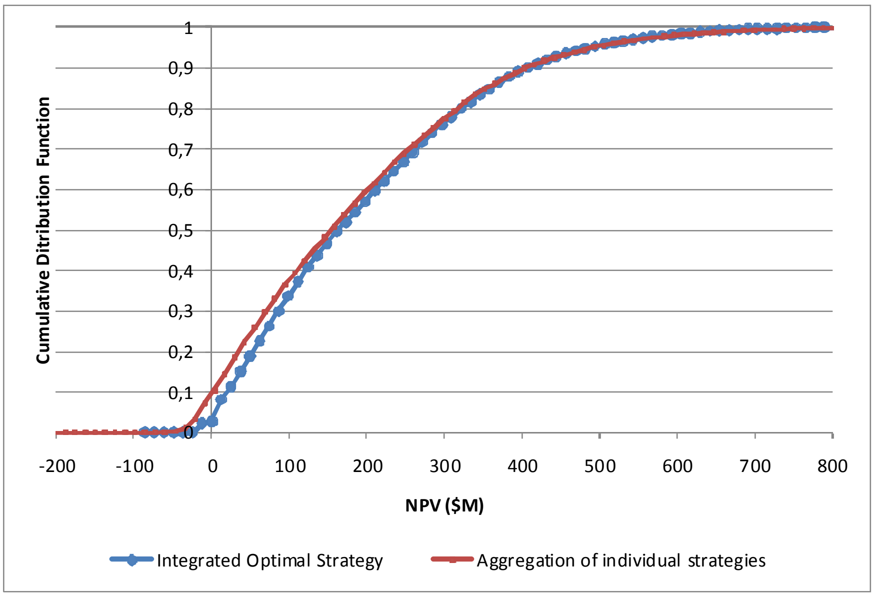

Figure 11 – NPV cumulative distribution function for both strategies

Figure 11 presents the cumulative distribution functions for the NPV of each strategy. The first thing to notice is that the integrated strategy has a first order dominance over the aggregation strategy, as their cumulative distribution functions never cross. If the behaviors of the two strategies toward risk are the same for high positive NPV (risk to earn money by avoiding negative outcomes), they are different regarding low and negative NPVs. The minimal NPV for the integrated strategy is -$80M, as for the aggregation strategy it can go down to -$200M. The two reasons for having a negative NPV are:

1. Making an investment that will not avoid anything, as nothing would have happened with or without this investment. It is usually responsible for stairs in the shape of the cumulative distribution function, for negative NPV, as it can be seen in Figure 12 which is a zoom of Figure 11.

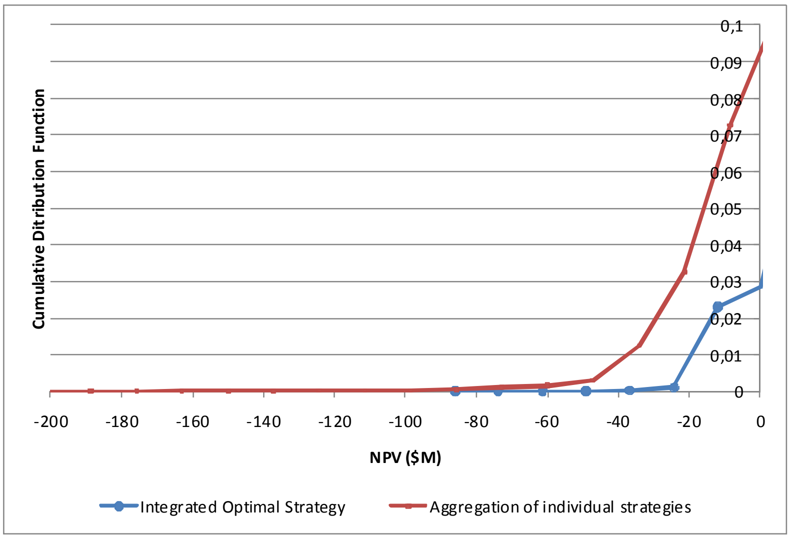

Figure 12 – Negative part of the NPV cumulative distribution function for both strategies

2. The second source of negative NPV is the cases for which making the investment will actually create unwanted consequences such as failures. It usually corresponds to the minimal values of the NPV cumulative distribution function.

In the case of the integrated strategy, the probability of regret is lower because there are only two investments made (component A and spare part) compared with the five individual strategies, that is to say the cost of investment is lower, and the integrated strategy will not create bad outcomes for components B, C and D as they are not directly impacted by this strategy (the fact that the spare part could be used to replace on failure one of this component and fail again is a possibility but is a second order one).

This test case showed the importance of an Integrated Life Cycle-Management as the aggregation of independent LCM plans may lead to situations that are less profitable and more exposed to risk.

4.4. Decisions robustness

One important thing to do when carrying out an Integrated Life Cycle-Management study is to analyze the sensitivity of the results to variations of certain parameters. As a matter of fact there are two sources of uncertainty in this kind of studies:

- The first one is the aleatoric uncertainty on failure dates; this type of uncertainty is directly taken into account in IPOP as being the risk source. It is modeled through a reliability law in the quantification process.
- The second one are all epistemic uncertainties due to lacks of knowledge, these uncertainties may impact all parameters of the study, including the parameters of the reliability law modeling the aleatoric uncertainty on failure dates, but also costs or supply delays… This kind of uncertainty is not modeled in IPOP, but the robustness of optimal decisions are analyzed by making sensitivity studies, that is to say modifying some parameters and comparing the new results with the nominal ones in order to evaluate their robustness.

On this particular case a sensitivity analysis was made on the failure rates, two alternate studies were carried out with all failure rates multiplied by a factor 2 (worst case) and divided by 2 (best case). Table 4 presents the optimal strategies for the three universe of input data. The first thing to notice is the variation of the optimal NPV, it is a decreasing function of the reliability of the components, which is logical as for very reliable components the numbers of failures to avoid, that is to say possible profits of making a preventive investment, is low.
As for the robustness, all decisions are robust to uncertainty on the components reliability, except for component A. Whatever the reliability is, the optimal solution is still to purchase a spare part as soon as possible and to make no replacement on components B, C and D.

	Component A	Component B	Component C	Component D	Spare Part	Global NPV
Integrated Optimal strategy – Worst Case	2010				2010	$276.8M
Integrated Optimal strategy – Nominal Case	2013	-	-	-	2010	$199.5M
Integrated Optimal strategy – Best Case	-	-	-	-	2010	$106.2M

Table 4 – Strategies risk assessment

Another way to look at the sensitivity is to evaluate all three strategies in all three reliability universe. It is then possible to answer questions like “How bad would be my decision made with an assumption on the reliability if this assumption happened to be false”. Table 5 and Table 6 present the optimal NPVs and risk indicator for the three different strategies in the three cases of reliability. The risk indicator is the probability to have a long forced outage because of spare part unavailability. A quick analysis of these results shows that, except in its own universe in which it is of course optimal (green), the best case strategy is a bad decision in terms of mean NPV as it is ranked number 3 (red) in the worst case universe and the nominal case universe. If we look at the risk indicators, this strategy is ranked number 3 in all three universes (even though it remains acceptable in the best case universe). The best case strategy seems to be a risky choice that should be taken if the best case reliability hypothesis is very likely to be correct. With the same kind of analysis on the other strategies, the nominal case strategy would be recommended as it is ranked number 2 (orange) in the worst case and best case universes and because postponing the replacement from 2010 (worst case strategy) to 2013 (nominal case strategy) has very little impact on the risk of long forced outage whatever the reliability universe is.

	Worst case optimal strategy	**Nominal case optimal strategy**	**Best case optimal strategy**
Worst case reliability universe	\$276.8M	\$275.9M	\$271.4M
Nominal case reliability universe	\$199.3M	\$199.5M	\$197.4M
Best case reliability universe	\$103.6M	\$104.7M	\$106.2M

Table 5 – NPV robustness

	Worst case optimal strategy	**Nominal case optimal strategy**	**Best case optimal strategy**
Worst case reliability universe	11.6%	11.5%	16.6%
Nominal case reliability universe	16.1%	16%	10.4%
Best case reliability universe	1.7%	1.8%	3.4%

Table 6 – Robustness of the risk indicator of long forced outage

In conclusion of this sensitivity study, the most robust strategy to reliability models uncertainty is:

- Purchase a spare part in 2010
- Make a preventive replacement of component A in 2013
- Make no preventive replacement of the other components

5. CONCLUSION

This paper presented IPOP software and how it could be used, in association with a Likelihood of Failure database, to perform Integrated Life-Cycle Management (ILCM) studies. In this first version of the tool, optimization is made on average indicators; the risk-informed valuation function is only used a posteriori to calculate risk indicators of the optimal solution, which the PDMP cannot evaluate. But the test-case presented here showed the importance of such probabilistic assessments in the decision making process. This is why it would be a very interesting feature of the tool to use such indicators as a goal function or constraints in the optimization module. In the future years, methodological works will be made to plug the optimization algorithm and the Monte-Carlo simulation to be able to make this kind of simulations. Closer from now, new features, based on fractional factorial design of experiments theory, will be added to automate sensitivity analysis.

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