Post-warranty Maintenance Strategy Selection Using Shape Packages Process

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Abstract

It is fair to assume that selection of a post-warranty maintenance strategy is one of the main challenges the capital-good owners face; however, there is relatively little research done in this area. This paper aims to assist asset owners in selecting the equipment maintenance package at the warranty termination time; it proposes the shape package process (SPP), which represents a comprehensive process that facilitates the choice between multiple packages, considering the cost and risk associated with each package.

The main novelty of this paper is introducing two new parameters to compare maintenance packages: the risk reduction factor (RRF) to assess the maintenance task effectiveness in reducing non-financial risk and the value-added indicator (VAI) to evaluate the task efficiency in reducing the financial risk. Additionally, the suggested process includes mapping the risk profile associated with each package, enabling a cost-cutting process where the tasks with less value and risk mitigation can be easily identified and eliminated.

A case study then demonstrates the process flexibility in comparing different maintenance packages using the analytical hierarchy process (AHP); while presenting RRF and VAI at the task and package levels when implemented in a cooling water system to select the post-warranty maintenance package from an asset owner's perspective.

Keywords: Post-warranty, maintenance strategy, analytical hierarchy process, case study

1. Introduction

In today's production plants, warranty agreements, long-term maintenance and service contracts play a significant role in determining the asset life cycle cost and, most importantly, in shaping the operational risk profile. One of the critical decisions equipment owners should take at the end of the warranty period is whether to extend the warranty agreement or look for other decision options such as in-house maintenance, a long-term maintenance contract or a combination of both where the corrective maintenance is performed via in-house resources while the preventive maintenance is outsourced [1, p. 66]. For instance, the civil aviation industry spent more than $60B in 2013 on aircraft maintenance; therefore, outsourcing part of the maintenance activities is needed in order to reduce the airlines operating expenditures and increase competitiveness. So there is a need for a combination of in-house and outsourced maintenance activities [2, p. 127].

Also, there is an increasing trend of promoting extended warranty contracts [3, p. 266], so the organisation might receive several offers from various maintenance service providers. In this case, a standard process is required to enable stakeholders to compare packages and negotiate the optimum extension scope. On the other hand, extending those contracts is not always available as an option, as the original equipment manufacturer tends to outsource the warranty services when there is high market competition [4]. Moreover, it is not always possible to reach a win-win warranty extension agreement between the manufacturer and the asset owner as it depends on maintenance strategy, repair cost and task frequency [5, p. 848]. Additionally, several reasons, such as budget and logistics, might force the equipment owners to move toward in-house maintenance. This move requires a standard process to help the plant maintenance team prepare the post-warranty maintenance packages and eliminate the low-value-added tasks. In summary, asset owners need a well-structured process to make the right decisions and hence sustain reliability and availability at the end of the warranty period.

This paper proposes an approach to assess warranty extension feasibility and compare maintenance packages to select the ideal one from the equipment owner's point of view at the warranty termination time. The proposed approach uses the classical established methods of Failure modes and effect analysis (FMEA) and analytical hierarchy process (AHP). The AHP is chosen as a multi-criteria decision-making tool amongst several viable alternative methods (e.g. Best Worst Method, Fuzzy AHP, Electre, Promethee). This is because (i) AHP is a well-established method [6, p. 1] that has stood the test of time, and hence is more likely to be accepted by equipment owners (ii) the available data in the shape packages process is crisp rather than fuzzy and hence introducing the additional complexity of a fuzzy method would be counterproductive, and the same argument applies for the rationale of using classical FMEA rather than its fuzzy version (iii) the equipment owner can only implement a single maintenance strategy and hence needs a selection rather than a ranking technique such as the Electre method [7] (iv) the number of pairwise comparisons needed is not onerous and hence there is no need to resort to a method with a reduced number pairwise comparisons, such as the best-worst method. Finally, (v) the AHP has an inbuilt measure of inconsistency [8] to give the equipment owner confidence in their choice of maintenance strategy. Hence, the AHP method is chosen as the preferred multiple criteria decision-making tool.

2. Literature Review

This paper aims to complement the authors' previous work, in which they proposed a conceptual framework of eight fundamental processes for an agile asset performance management system; the work concentrated on the interrelationship and connections between the processes to demonstrate the framework integrity with less focus on the processes design [9]. Hence, this paper introduces the detailed structure for one of these processes (Shape Packages) along with its application in maintenance strategy selection for the post-warranty period, which is the responsibility of the asset owner as the warranty contracts limit the manufacturer's commitment to the warranty period [10, p. 653]. There are many frameworks created for asset strategy development; also, several approaches have been introduced for post-warranty maintenance program selection from a warrantor standpoint. But there is less research work that addresses the post-warranty challenge from a capital-good owner's perspective; therefore, this work attempts to fill this gap [11, p. 299].

Several research papers have highlighted the importance of the post-warranty maintenance strategy and its impact on: asset life cycle cost [12], the expected total cost to the manufacturer [13, p. 565] and the maintenance cost-effectiveness [14, p. 139]. Therefore, the post-warranty maintenance problems [10, p. 669], the optimal post-warranty maintenance strategy under a non-renewal warranty [12, p. 9], the need for customised warranty programs [15, p. 11], and the use of different maintenance policies under different conditions to optimise the preventive maintenance level for a repairable product under warranty [16]; all have been suggested as interesting areas for future research. Furthermore, the authors have highlighted the need for further research to create a methodology that determines the competing maintenance packages' relative importance and defines the return on investment at the maintenance action and package levels, considering stakeholders' expectations regarding risk reduction and cost-cutting [9]. In response to these needs, this paper proposes two metrics (RRF and VAI) that facilitate comparing different maintenance packages and demonstrate each maintenance action's importance, allowing further package improvement by eliminating the actions with insignificant RRF and VAI. Compared to other metrics used in similar frameworks [17], the RRF and VAI have the advantage of using a simplified mathematical model that does not require advanced tools/ software to implement, making the process more practical and straightforward to be adopted by asset owners and practitioners.

Furthermore, the case study section demonstrates how the RRF and VAI facilitate the use of the AHP, as selecting equipment optimum maintenance strategy is a multiple criteria decision-making process [18, p. 160]. Additionally, the RRF and VAI consider the different influential parameters, such as repair time, repair cost, asset degradation rate, asset usage rate, market demand, asset owner's risk appetite, operational and business decisions. We will now critically discuss the literature related to each of the identified influential parameters.

Repair time is essential to identify the optimal post-warranty maintenance policy, as most of the existing warranty policies do not cover the downtime loss [19, p. 153]. Hence, the optimisation of the repair activities is a crucial parameter to consider during the development of a reliability model [20]. Also, ***repair cost*** is one of the key elements in deciding the optimal preventive maintenance frequency during the post-warranty period [21, p. 184]. As the highly deteriorated assets with high repair costs need more PM's during the post-warranty period [22], there is a need for flexible PM policies that consider the downtime loss [23].

Asset degradation and usage rates are significant factors to consider when optimising the extended warranty cost [24, p. 5778], as "When the machine deteriorating rate increases, the times of the maintenance actions increase" [25, p. 13]. Also, the numerical results show the higher degree of asset deterioration, the higher the optimal maintenance frequency and cost increases [26, p. 1088] [27, p. 799]. Hence, the manufacturer's flexible maintenance packages that consider the usage rate achieve more cost optimisation when compared with time-based and usage-based PM strategies [28, p. 86], which justifies the need for different warranty extension packages to consider the various asset degradation and usage rates [29, p. 99].

Market demand fluctuation is an additional factor to consider in maintenance strategy optimisation, and there is a need for a consolidated optimisation approach for production and maintenance [30, p. 6434] in which the maintenance decisions consider the production schedule, quality procedure, product cost and poor quality [31, p. 1055].

The asset owner's risk appetite is an influential factor in the post-warranty maintenance package selection as the risk criteria can vary from plant to plant, depending on their exposure and tolerance to absorb the facility shutdown's consequences [32, p. 72]. On the other side, the warrantor's risk appetite influences the length of the offered extended warranty as it brings various risks that can significantly impact their profits [33, p. 1104]. Hence, stakeholders' risk appetite is different when assessing the maintenance cost and post-warranty period risk [34, p. 569].

The ***operational and business decisions*** are crucial to the maintenance package selection as the OEM recommended maintenance intervals can be modelled as a function of the operational decisions [35]. However, there are three dimensions for business decisions: resources, output, and risk. The output dimension considers meeting the operational, safety, and environmental objectives, while the risk dimension considers the financial and non-financial consequences of unplanned incidents and unexpected failures [36, p. 289]. Still, there is a need to quantify and optimise those three dimensions [37, p. 383], and the suggested SPP in this paper introduces two numerical indicators to address this need for quantification as an extension of the warranty attractiveness index idea [38, p. 429].

The main contribution of this paper is that it addresses the post-warranty maintenance strategy selection problem from a capital-good owner/operator point of view, where there is an absence of a systematic approach to make decisions on how to sustain capital goods after their warranty period expires, and this paper fills this gap. Hence, it is believed that the proposed framework has the potential to have a significant impact in practice.

3. Shape Packages Process (SPP)

This section explains the proposed shape packages process (SPP) as coined by the authors in their previous research [9], as it facilitates the formation of different maintenance packages that suit different operating context scenarios for the same asset. The process starts with selecting and prioritising the assets; then, it develops a list of actual and potential failure modes for high-priority assets using the computerised maintenance management system (CMMS) data and stakeholder experience. The developed list is then linked to the maintenance tasks to identify the value-added and the risk reduction by each maintenance package so the stakeholder can take an informed decision, as detailed in the following sections.

3.1. Assets selection and prioritisation for SPP

The authors have created the criteria proposed in Figure 1 and coined it the "post-warranty prioritisation grid". The grid depicts the suggested assets' selection and prioritisation criteria for SPP considering two dimensions; the first dimension is the maintenance contract cost, while the second is the equipment criticality dimension which has three levels varying from "A" representing the highly critical assets to the "C", which means the lowest criticality assets. This ABC indicator [39, p. 1] represents the most common industry practice adopted by the market-leading CMMS providers. Hence it can be safely assumed that it applies to different maintenance scenarios, where the equipment criticality is determined considering the asset failure consequences on the various business aspects like safety, environment, operation, financial...etc. This criticality indicator enables asset owners to prioritise improvement initiatives and day-to-day activities and facilitates the creation of criticality-based KPIs [40, p. 1].

The grid considers all assets approaching the end of the maintenance and warranty contract, where the asset owners must decide whether to extend the contract or proceed with a post-warranty maintenance package developed in-house or proposed by a different maintenance service provider.

The grid assigns priority five (the highest priority) to the "A" critical assets with a high-cost maintenance contract. On the other hand, the "C" critical assets with a low-cost contract are given the lowest priority for review under SPP. Priority four is dedicated to the "B" critical assets with a high-cost maintenance contract and the "A" critical assets with moderate maintenance cost. Then, priority two is assigned to the "B" critical assets under a low-cost contract. The same priority is given to the "C" critical assets under a moderate cost contract. Lastly, priority three is assigned to the "A" critical assets under a low-cost maintenance contract, "B" critical assets under a moderate cost contract, or "C" critical assets under a high-cost contract.

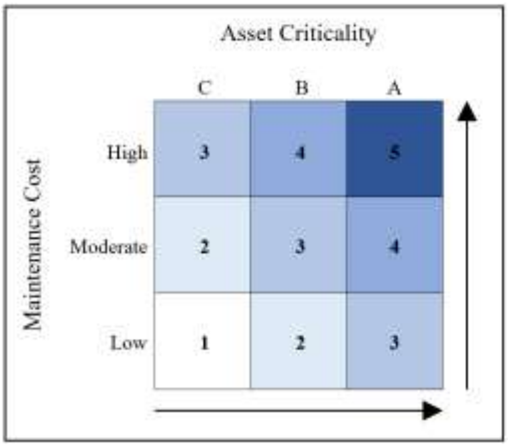


Figure 1:Post-warranty prioritisation grid

The suggested selection and prioritisation grid enables stakeholders to sort assets rationally, creating a reasonable priority list where the assets are sequenced to implement the steps introduced in the SPP flowchart.

3.2.SPP flowchart

As depicted in Figure 2 for the selected high-priority asset, the SPP starts by forming a consolidated failure mode list that combines failure modes that have happened before based on CMM records and failure modes that have never occurred to the selected asset; however, the analysis team consider it reasonably likely to happen. For instance, if the CMMS records indicate five failure events due to three different failure modes, one of which is repeated three times, then the consolidated failure mode list will have three failure modes besides any additional potential failure modes proposed by the team. The analysis team is a cross-functional team formed from the different stakeholders to propose reasonably likely failure modes' and assess the inherent and residual risk. The team also suggests a post-warranty maintenance package against the warranty maintenance package in place. There are several probable sources of the suggested post-warranty maintenance package, such as:

- Reliability-centred maintenance (RCM) study; which is a commonly accepted methodology for developing a functional-based maintenance package for critical systems [41].

- Failure modes and effect analysis (FMEA); is widely used for creating an equipment-based maintenance package for moderate criticality equipment [42]. Also, failure modes, effects and criticality analysis is the most commonly utilised tool for estimating warranty risk in the automotive industry [43, p. 6].
- Maintenance packages that are offered by different service providers.
- Or it can be developed by the analysis team based on their relevant experience.

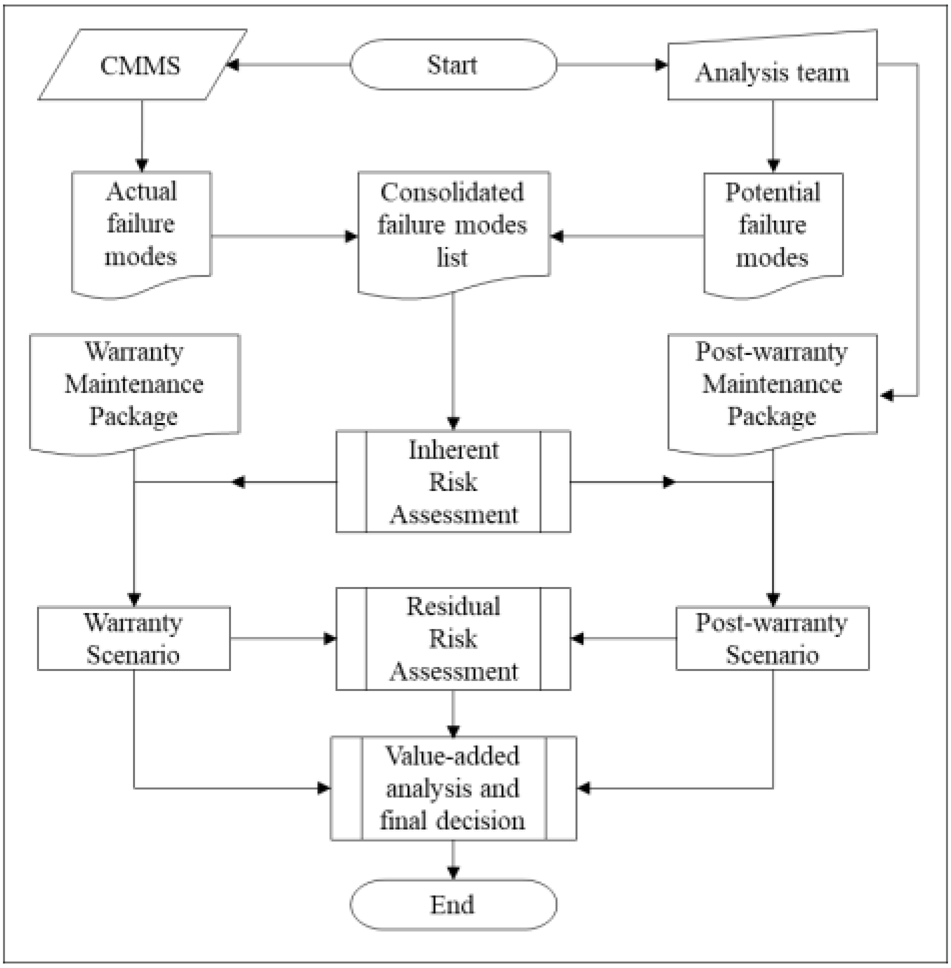


Figure 2: SPP flowchart

Once the consolidated failure mode list is prepared, the analysis team can proceed with the inherent risk assessment step to quantify the risk of every failure mode, assuming no maintenance. During this step, the team uses the CMMS records to guide the likelihood assessment of the actual failure modes, so the most repeated failure modes are assigned higher likelihood compared to other failure modes with less frequency or that have never occurred before (potential failure modes). This need to establish a criticality indicator for each failure mode based on frequency and consequences has also been highlighted by Viveros, Nikulin, López-Campos, Villalón and Crespo (2018) during their research to define a methodology for the resolution of reliability problems based on failure mode analysis [44, p. 1229]

Following the general guidelines for selecting appropriate risk assessment techniques [45, p. 675], the SPP employs the quantitative FMEA technique as a risk assessment methodology for asset maintenance decision-making, using the four risk categories recommended by ISO 14224 for failure consequences classification: safety, environmental, operational, and production [46]. As depicted in Figure 3, the analysis team assesses the likelihood and consequences of the worst-case scenario for each failure mode. For instance, in failure mode 4, the team assumes that the worst-case scenario is unlikely (0.001) to happen, and if it occurs, it will have minor (10) consequences on safety; hence the inherent safety risk will be (0.01), as shown in Table 1. Following the same steps, the team can assess the inherent risk for the environment and operation risk aspects. Safety, environmental and operation risks represent the non-financial risk; on the other side, the financial risk includes the repair cost, production loss, and any additional economic consequences of failure, as explained in the following sections. These four risk aspects cover the different evaluating losses identified by Tsutsui and Takata (2012) in their life cycle maintenance planning method, in which they considered the integration of maintenance and operation [47, p. 190].

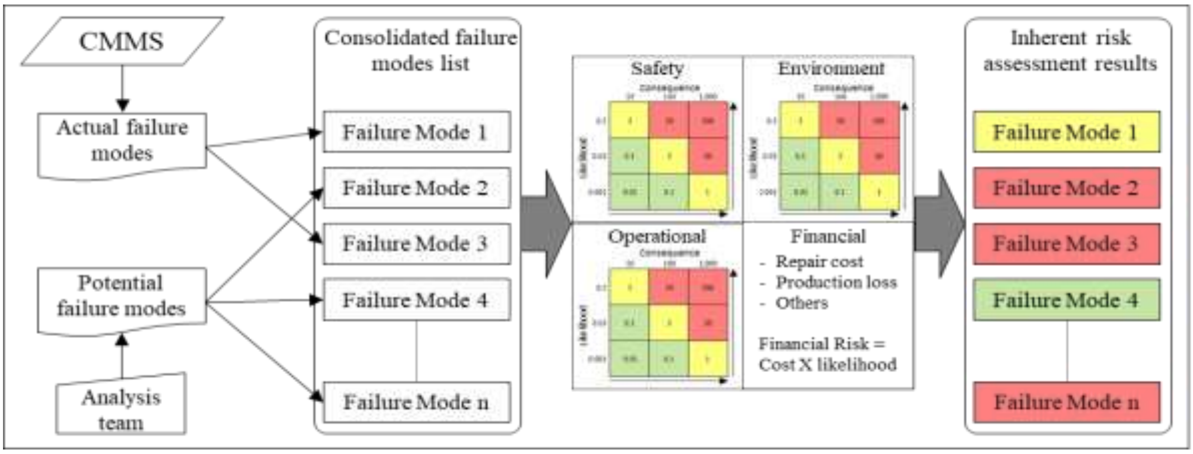


Figure 3: Inherent risk assessment step

Yunusa-Kaltungo and Labib (2020) have highlighted the need "for developing a framework that systematically segregates maintenance strategies according to individual asset performance" [48, p. 9]. Also, as recommended by many risk management practices and standards, "risk assessment should be conducted systematically" [49, p. 11]. Hence, many organisations have internal procedures that mandate using the same risk assessment tool across all the organisation's activities; these procedures provide a detailed description of the tool and its application. As the risk matrix has been widely accepted and adopted by many organisations as their preferred risk assessment tool, SPP has been designed to increase the alignment and integration with the organisation's procedures and work processes. This gives a significant advantage to the risk matrix over the traditional RPN (risk priority number) method as a risk assessment tool in the SPP process.

This paper proposes a risk matrix in Figure 3 with four aspects: safety, environment, operational, and financial, which covers the three business decision dimensions identified by Tam and Price (2008). The first three aspects are to be assessed by a 3 × 3 matrix where the consequence and likelihood have three levels, while the financial risk is assessed by multiplying the event likelihood by the total failure cost. The total failure cost includes the summation of the production loss amount, repair cost, regulatory fines and the cost of rectifying any safety and environmental damage. The analysis team estimates the production loss amount considering the total downtime, production rate and gross profit per unit; on the other side, the repair cost estimation covers spare parts and labour expenses.

Table 1 provides a detailed illustrative example of the inherent risk assessment step. The example assumes an asset with n number of failure modes where FM_1, FM_2, FM_3, FM_4 and FM_5 refer to failure modes such as bearing failure, seal leak, ...etc. For each failure mode, the worst-case failure scenario is considered while assessing the safety, environmental, operational and financial risks; then, the non-financial inherent risk and the financial inherent risk are calculated to facilitate prioritisation and improvement efforts.

Table 1: Inherent risk assessment illustrative example

FM	**Inherent Risk Assessment**															
	Safety (S)			**Environment (E)**			**Operation (O)**			**NFIR**	**Financial (F)**					**FIR**
	L	**C**	**IR**	**L**	**C**	**IR**	**L**	**C**	**IR**		**L**	**RC $**	**PL $**	**OL $**	**RC+PL +OL**	
FM_1	0.03	100	3	0.001	10	0.01	0.03	10	0.3	**3.31**	0.001	15,000	1,000	-	16,000	**16**
FM_2	0.03	10	0.3	0.03	100	3	0.03	100	3	**6.3**	0.5	15,000	1,000	-	16,000	**8,000**
FM_3	0.03	10	0.3	0.001	10	0.01	0.5	10	5	**5.31**	0.03	150,000	5,000	-	155,000	**4,650**
FM_4	0.001	10	0.01	0.03	10	0.3	0.03	10	0.3	**0.61**	0.03	250,000	5,000	-	255,000	**7,650**
FM_n	0.001	10	0.01	0.001	10	0.01	0.5	100	50	**50.02**	0.001	200,000	5,000	-	205,000	**205**

The notations used in the table are:

FM : Failure Mode
L : Likelihood
C : Consequence
IR : Inherent Risk
NFIR : Non-financial Inherent Risk
FIR : Financial Inherent Risk
RC : Repair Cost
PL : Production Loss
OL : Other losses

For a given failure mode FM_n the safety, environment and operation inherent risks can be assessed by multiplying the likelihood and the consequence of the worst-case failure scenario, assuming zero-based maintenance (no maintenance package in place), as per equations (1), (2) and (3):

$$SIR_{FM_n} = SL_{FM_n} \times SC_{FM_n} \tag{1}$$

SIR_{FM_n}: the safety inherent risk of failure mode n, assuming zero-based maintenance.

SL_{FM_n}: the likelihood of failure mode n safety consequences, assuming zero-based maintenance.

SC_{FM_n}: the safety consequences of failure mode n, assuming zero-based maintenance.

$$EIR_{FM_n} = EL_{FM_n} \times EC_{FM_n} \tag{2}$$

EIR_{FM_n}: the environmental inherent risk of failure mode n, assuming zero-based maintenance.

EL_{FM_n}: the likelihood of failure mode n environmental consequences, assuming zero-based maintenance.

EC_{FM_n}: the environmental consequences of failure mode n, assuming zero-based maintenance.

$$OIR_{FM_n} = OL_{FM_n} \times OC_{FM_n} \tag{3}$$

OIR_{FM_n}: the operational inherent risk of failure mode n, assuming zero-based maintenance.

OL_{FM_n}: the operational event likelihood of failure mode n, assuming zero-based maintenance.

OC_{FM_n}: the operational consequences of failure mode n, assuming zero-based maintenance.

Then, the non-financial and financial inherent risks are calculated as per equations (4) and (5):

$$NFIR_{FM_n} = SIR_{FM_n} + EIR_{FM_n} + OIR_{FM_n} \tag{4}$$

$NFIR_{FM_n}$: The non-financial inherent risk of failure mode n

$$FIR_{FM_n} = FL_{FM_n} \times (RC_{FM_n} + PL_{FM_n} + OL_{FM_n}) \tag{5}$$

FIR_{FM_n} : The financial inherent risk of failure mode n, assuming zero-based maintenance.

FL_{FM_n} : The financial loss likelihood of failure mode n, assuming zero-based maintenance.

RC_{FM_n} : The repair cost of failure mode n, assuming zero-based maintenance.

PL_{FM_n} : The production loss of failure mode n, assuming zero-based maintenance.

OL_{FM_n} : Other losses of failure mode n, assuming zero-based maintenance.

For instance, in the case of failure mode 1, the inherent risk figures are calculated as follows:

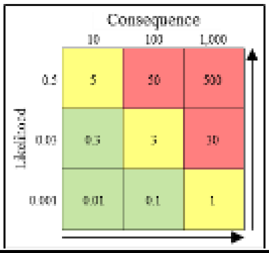
$$Safety\ inherent\ risk\ (SIR) = Likelihood\ (L) \times\ Consequence(C) = 0.03\ \times 100 = 3$$

$$The\ non\text{-}financial\ inherent\ risk\ (NFIR) = SIR + EIR + OIR = 3 + 0.01 + 0.3 = 3.31$$

$$\begin{aligned} &The\ financial\ inherent\ risk \\ &\qquad = Likelihood \times [Repair\ cost(RC) + Production\ loss(PL) + other\ losses\ (OL)] \\ &\qquad = 0.001 \times 16{,}000 = 16 \end{aligned}$$

The authors have analysed different methods to calculate the non-financial risk values, such as the summation, the multiplication, and the highest category. The summation method provides more rational results when compared to other options. Table 2 compares the three methods when used to calculate the non-financial risk for three failure modes A, B, and C.

Table 2: non-financial risk calculation options

Failure Mode	Risk value			Calculated non-financial risk			
	Safety	Environment	Operational	Summation	Multiplication	The highest	
A	5	3	3	11	45	5	
B	5	1	0.01	6.01	0.05	5	
C	3	3	3	9	27	3	

As indicated in the table, the highest method allocates the same non-financial risk value to failure modes "A" and "B"; however, "A" has a higher environmental and operational risk. On the other side, the multiplication method calculates a higher non-financial risk for failure mode "C" than "B"; failure mode B has a higher safety risk. Also, considering the used risk matrix, which has three clusters: red, yellow, and green, the multiplication method moves the failure mode risk to a higher cluster as in failure modes "A" and "C".

At the end of the inherent risk assessment step, each failure mode is assigned an inherent non-financial and financial risk value which is an input to the scenario development step. The inherent risk assessment shall be reviewed and updated periodically to consider the asset deterioration conditions, which accommodate the needs highlighted by Shahanaghi et al. (2013). The frequency of these periodic reviews should be the same as the maintenance strategy cycle; in other words, all the maintenance strategy actions shall be executed at least once before commencing the review process. For example, suppose the lowest frequency action is to be implemented every five years. In that case, the inherent risk review cycle will be five years to assure the execution of all actions before evaluating and amending the inherent risk and maintenance package. Besides the periodic review, the authors have addressed the need for immediate risk and action updates in response to operating context transitions and failure rate changes [9].

Figure 4 depicts the steps of building the *status quo* scenario (the current warranty scenario) and the proposed post-warranty scenario. The first step in building each scenario is to link each maintenance task with the failure modes it mitigates. Besides the warranty and post-warranty scenarios, there is no limitation on the number of scenarios that can be analysed using the SPP process.

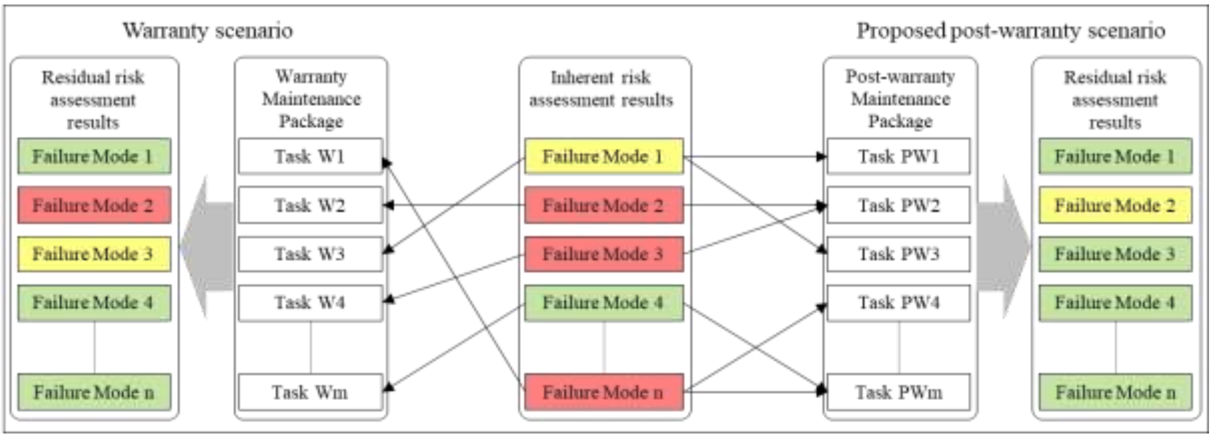


Figure 4: Residual risk assessment step

The analysis team then assess the residual risk to compare the warranty maintenance package and the proposed post-warranty maintenance package, as indicated in Table 3. The residual risk assessment step aims to evaluate the proposed maintenance task effectiveness in reducing the failure mode inherent risk, so the risk assessment is performed assuming the execution of the proposed task, and the team evaluates how far the task reduces the failure mode likelihood or consequences.

Table 3: Residual risk assessment illustrative example

Warranty Scenario						**Inherent Risk Assessment Results**			**Proposed post-warranty scenario**					
Task	**Residual Risk Assessment**					**FM**	**NFIR**	**FIR $**	**Task**	**Residual Risk Assessment**				
	SRR	**ERR**	**ORR**	**NFRR**	**FRR $**					**SRR**	**ERR**	**ORR**	**NFRR**	**FRR $**
W_3	0.1	0.01	0.3	0.41	13	FM_1	3.31	16	PW_1	0.1	0.01	0.01	0.12	11
									PW_3	0.1	0.01	0.3		
W_2	0.01	3	3	6.01	480	FM_2	6.3	8,000	PW_2	0.01	0.1	3	3.11	450
W_4	0.3	0.01	3	3.31	3,150	FM_3	5.31	4,650	PW_2	0.01	0.01	0.3	0.32	155
W_m	0.01	0.3	0.01	0.32	6,750	FM_4	0.61	7,650	PW_m	0.01	0.3	0.01	0.32	255
W_1	0.01	0.01	0.1	0.12	185	FM_n	50.02	205	PW_4	0.01	0.01	0.1	0.12	155
									PW_m	0.01	0.01	3		

The notations used in the table are:

FRR : Financial Residual Risk
NFRR : Non-financial Residual Risk
ORR : Operation Residual Risk
ERR : Environment Residual Risk
SRR : Safety Residual Risk

For a given task TK_m :

$$SRR_{TK_m} = SL_{TK_m} \times SC_{TK_m} \tag{6}$$

SRR_{TK_m} : the safety residual risk of failure mode, considering the execution of task m.

SL_{TK_m} : the safety likelihood of failure mode, considering the execution of task m.

SC_{TK_m} : the safety consequences of failure mode, considering the execution of task m.

$$ERR_{TK_m} = EL_{TK_m} \times EC_{TK_m} \tag{7}$$

ERR_{TK_m} : the environmental residual risk of failure mode, considering the execution of task m.

EL_{TK_m} : the environmental event likelihood of failure mode, considering the execution of task m.

EC_{TK_m} : the environmental consequences of failure mode, considering the execution of task m.

$$ORR_{TK_m} = OL_{TK_m} \times OC_{TK_m} \tag{8}$$

ORR_{TK_m} : the operational residual risk of failure mode, considering the execution of task m.

OL_{TK_m} : the operational event likelihood of failure mode, considering the execution of task m.

OC_{TK_m} : the operational consequences of failure mode, considering the execution of task m.

$$NFRR_{TK_m} = SRR_{TK_m} + ERR_{TK_m} + ORR_{TK_m} \tag{9}$$

$NFRR_{TK_m}$: The non-financial residual risk of task m

$$FRR_{TK_m} = FL_{TK_m} \times (RC_{TK_m} + PL_{TK_m} + OL_{TK_m}) \tag{10}$$

FRR_{TK_m} : The financial residual risk of task m

It is common to assume independent failure modes while using maintenance strategy development techniques such as FMEA and RCM, where “each failure mode is treated as independent." [42, p. 8]; similarly, SPP assumes independent failure modes and maintenance tasks during the residual risk assessment. For instance, in Table 3 failure mode FM1 has been mitigated by tasks PW1 and PW3, so the residual risk from task PW1 is assessed without considering the effect of task PW3, and the residual risk of FM1 is selected as the lowest score of the residual risks of the two corresponding tasks. The pros of considering the lowest score include streamlining the calculations of RRF and VAI, which facilitates the execution of the SPP by the practitioners; additionally, using the lowest score option simplifies the execution of what-if scenarios where the practitioner can easily see the impact of excluding any task on the risk profile as per figure 9. On the other side, the main cons of the lowest score method, it lacks the ideal representation of the risk profile when several tasks mitigate a single failure mode, as the profile will show only the effect of the task with the highest risk reduction.

Also, the authors have evaluated the idea of failure mode residual risk assessment while considering all mitigation actions, which seems more accurate from a theoretical perspective. However, there are critical practical challenges to encounter:

- the risk assessment step becomes more difficult as the practitioners must consider more than one mitigation action at a time which might lead to a poor assessment.
- the individual risk assessment of each mitigation action is still needed to enable the calculations of RRF and VAI, increasing the number of steps the practitioners should take.
- each time the practitioners eliminate or add new actions, a complete update of all the linked mitigated risk assessments is needed, which demands significant additional effort to maintain the SPP database.

For a failure mode n mitigated by a number of m failure modes:

$$NFRR_{FM_n} = \min(NFRR_{TK_1}\ , NFRR_{TK_2} \ldots\ldots\ldots, NFRR_{TK_m}) \qquad (11)$$

$NFRR_{FM_n}$: The non-financial residual risk of failure mode n, considering the execution of tasks 1, 2….and m.

$$FRR_{FM_n} = \min(FRR_{TK_1}\ , FRR_{TK_2} \ldots\ldots\ldots, FRR_{TK_m}) \qquad (12)$$

FRR_{FM_n}: The financial residual risk of failure mode n, considering the execution of tasks 1, 2….and m.

Then, for failure mode FM_1

$$NFRR_{PW_1} = SRR_{PW_1} + ERR_{PW_1} + ORR_{PW_1} = 0.1 + 0.01 + 0.01 = 0.12$$

$$NFRR_{PW_3} = SRR_{PW_3} + ERR_{PW_3} + ORR_{PW_3} = 0.1 + 0.01 + 0.3 = 0.41$$

$$NFRR_{FM_1} = 0.12 \text{ (the lowest value)}$$

Similarly, the financial residual risk (FRR) can be calculated by equations 10 and 12 using the financial likelihood (FL), RC, PL and OL assumptions.

$$FRR_{PW_1} = FL_{PW_1} \times \left(RC_{PW_1} + PL_{PW_1} + OL_{PW_1}\right) = 0.001 \times (10{,}000 + 1{,}000 + 0) = 11$$

$$FRR_{PW_3} = FL_{PW_3} \times \left(RC_{PW_3} + PL_{PW_3} + OL_{PW_3}\right) = 0.001 \times (11{,}000 + 1{,}000 + 0) = 12$$

$$FRR_{FM_1} = 11 \text{ (the lowest value)}$$

As depicted in Figure 2, the last step in SPP is the value-added analysis and the final decision. In this step, the authors extend the warranty attractiveness index idea proposed by Ambad and Kulkarni (2015) based on component cost and warranty policy type by introducing the risk reduction factor and the value-added indicator to consider the maintenance task cost and the risk it mitigates.

The risk reduction factor (RRF) is a percentage value between 0 and 100% that indicates how far the task effectively mitigates the failure mode non-financial risk; the higher the RFF, the more risk reduction the task delivers. For a task m (TK_m) that mitigates n number of failure modes, the RRF can be calculated by the following equation:

$$RRF_{TK_m} = 1 - \frac{\sum_{x=1}^{n} NFRR_{FM_x}}{\sum_{x=1}^{n} NFIR_{FM_x}} \tag{13}$$

RRF_{TK_m}: The risk reduction factor of task m

The value-added indicator (VAI) is a percentage value up to 100% as the value increases as the task (TK) is more effective in reducing the financial risk at a reasonable task annual cost (AC_{TK}). The below-proposed equation shows how the indicator is calculated.

$$VAI_{TK_m} = 1 - \frac{AC_{TK_m}}{\sum_{x=1}^{n}(FIR_{FM_x} - FRR_{FM_x})} \tag{14}$$

VAI_{TK_m}: The value-added indicator of task m

AC_{TK_m} : The annual cost of task m

Table 4 shows an illustrative example of the calculations. The inherent non-financial risk is the summation of the risk values for the safety, environmental, and operation aspects.

Table 4: Risk Reduction and Value-added Indicator calculations

FM	**NFIR**	**FIR**	**Task**	**TKAC**	**NFRR**	**FRR**	**RRF**	**VAI**
FM_2	6.3	8,000 $	TK_2	1,000$	3.11	450 $	70 %	92%
FM_3	5.31	4,650 $			0.32	155 $		

Finally, for all tasks, the risk reduction factors and value-added indicators are averaged at the maintenance package level using the following equations to enable the stakeholders to compare two packages or more and select the one that delivers the highest value.

For a package with m tasks:

$$PRRF = \frac{\sum_{x=1}^{m} RRF_{TK_x}}{m} \tag{15}$$

$$PVAI = \frac{\sum_{x=1}^{m} VAI_{TK_x}}{m} \tag{16}$$

$$PAC = \sum_{x=1}^{m} AC_{TK_x} \tag{17}$$

PRRF: Package Risk Reduction Factor
PVAI: Package Value Added Indicator
PAC: Package Annual cost

3.3. Sensitivity analysis

Table 5 shows the sensitivity analysis calculation for the risk reduction factor and the value-added indicator results introduced in Table 4.

Table 5:Sensitivity analysis calculations

Risk reduction factor (RRF) sensitivity calculations			Residual non-financial risk				
			80%	90%	**100%**	110%	120%
		70%	2.744	3.087	**3.43**	3.773	4.116
Inherent non-financial risk	80%	9.288	70%	67%	63%	59%	56%
	90%	10.449	74%	70%	67%	64%	61%
	100%	**11.61**	76%	73%	70%	68%	65%
	110%	12.771	79%	76%	73%	70%	68%
	120%	13.932	80%	78%	75%	73%	70%
Value-added Indicator (VAI) sensitivity calculations			Financial risk reduction				
			80%	90%	100%	110%	120%
		92%	14,454	13,250	**12,045**	10,841	9,636
Task annual cost	80%	1,200	*91.7%*	*90.9%*	*90.0%*	*88.9%*	*87.5%*
	90%	1,100	*92.4%*	*91.7%*	*90.9%*	*89.9%*	*88.6%*
	100%	**1,000**	*93.1%*	*92.5%*	*91.7%*	*90.8%*	*89.6%*
	110%	900	*93.8%*	*93.2%*	*92.5%*	*91.7%*	*90.7%*
	120%	800	*94.5%*	*94.0%*	*93.4%*	*92.6%*	*91.7%*

As indicated in Figure 5, the risk reduction factor increases as the inherent non-financial risk increases at a constant residual non-financial risk level. The risk reduction factor increases as the residual non-financial risk reduces at a constant inherent non-financial risk. In conclusion, as the task effectiveness in lowering the non-financial risk increases, its risk reduction factor increases.

Conversely, the value-added indicator increases as the annual task cost reduce at the same financial risk reduction level. Also, the value-added indicator increases as the financial risk reduction increase at the same task yearly cost. The yearly task cost can be reduced by reducing the task frequency; for instance, doing the task every six months instead of every three months reduces the annual task cost by 50%.

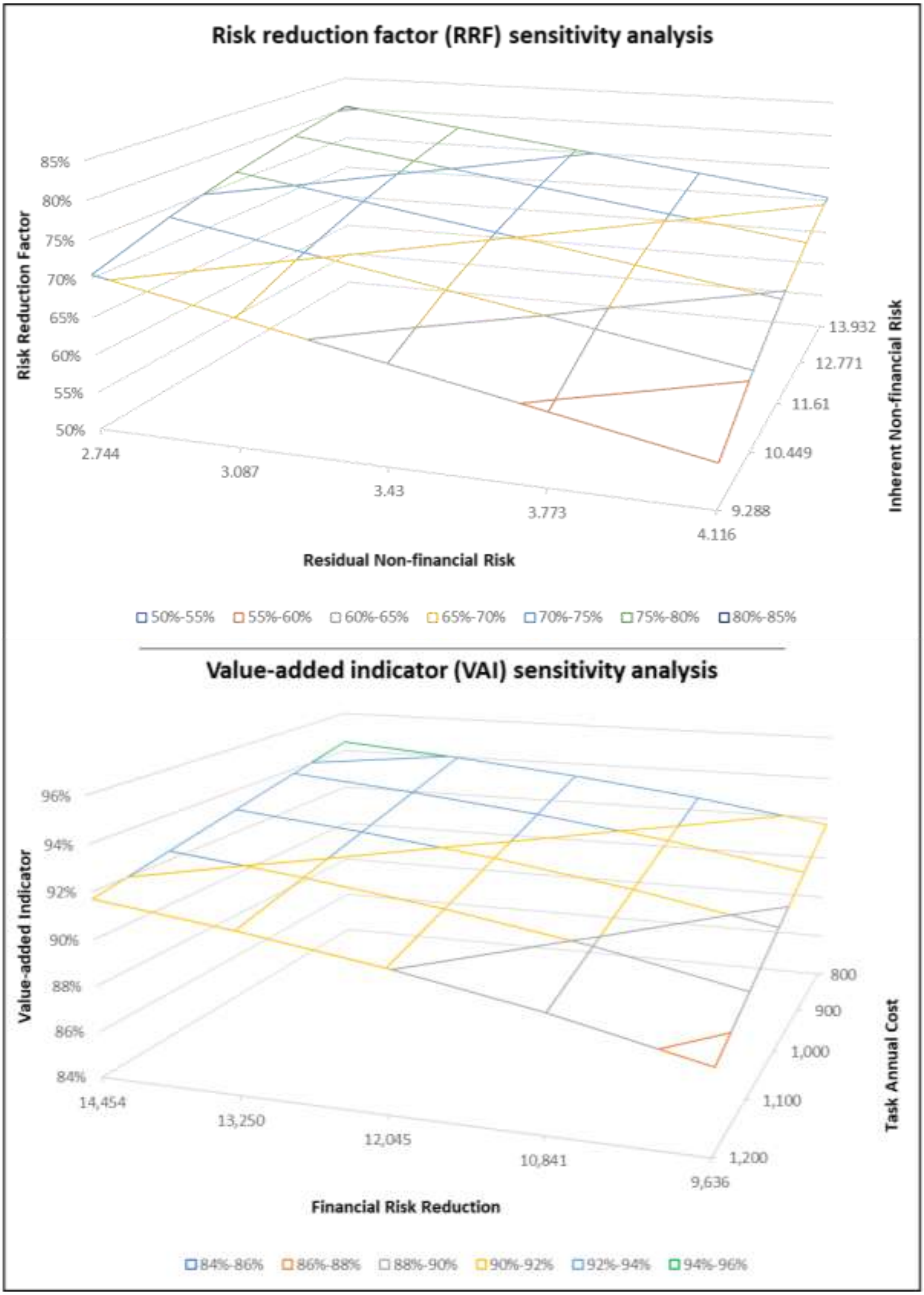


Figure 5: Sensitivity analysis of the illustrative example

4. Case Study

4.1. System Description

Cooling water systems are common in many industrial plants to remove waste heat from the processes. This case study considers a closed-loop system with a cross-exchange with seawater. The seawater system pumps the seawater through titanium plate and frame exchangers and returns it to the sea. The seawater pumps can also be used to pump seawater to the firewater system in an extreme emergency.

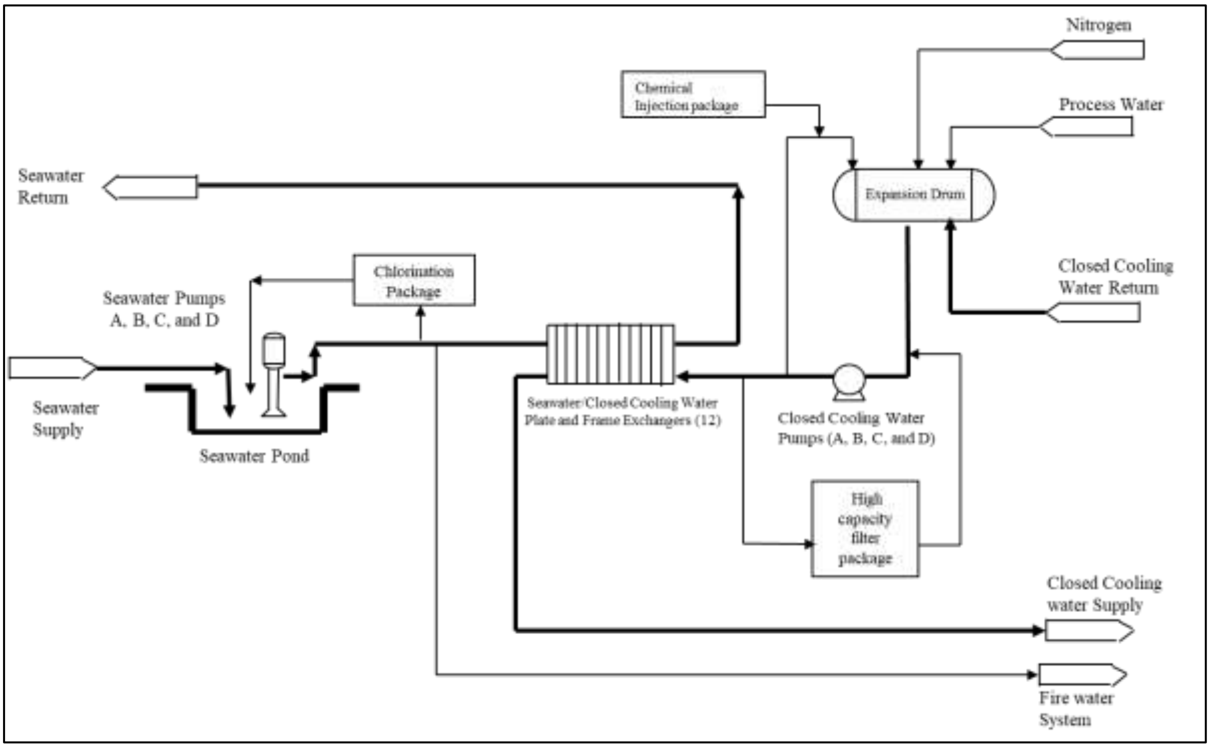


Figure 6: System Description

As depicted in Figure 6, the closed cooling water system function is to supply closed-loop cooling water circulation for waste heat removal. Key components of the system are the circulation pumps and expansion drum, which provides the water's surge capacity as it heats up. The drum also provides oil or gas separation in the event of an exchanger leak in the process units.

This case study discusses the implementation of SPP on a cooling water system within an oil and gas plant. The selected system was under a high-cost warranty agreement by the OEM, but this agreement is not extendable anymore, and the in-house maintenance or a global maintenance contract with a local provider are the only two available options. Also, the cooling water system is also classified as a highly critical asset based on the latest asset criticality analysis results [40]. Considering these facts and using the post-warranty prioritisation grid presented in Figure 1, this system will deem priority 5 for SPP. As explained above, the process will start with the closed cooling water pumps as key system components.

4.2. Closed cooling water pump SPP implementation

The implementation of SPP on the closed cooling water pumps follows the presented flowchart in Figure 2. The following sections use SPP to analyse the no-maintenance option (inherent risk assessment), warranty agreement, in-house maintenance, and local maintenance contractor packages.

4.2.1. SPP inherent risk assessment

a) Analysis team formation: A cross-functional team of the mechanical engineer, process engineer, HSE specialist, maintenance planner and cost controller have discussed and proposed the following list of the reasonably likely (potential) failure modes:

- **Bearing seizes** due to insufficient lubricant from the low-pressure supply.
- **Casing erosion** due to poor process quality
- **Shaft crack** due to stress corrosion cracking

b) CMMS: the maintenance planner has checked the failure history of the four pumps and found three failures happened before due to the below failure modes as documented in CMMS:

- **Impeller wears** due to cavitation from the off-BEP (Best Efficiency Point) operation.

- **Bearing fatigue** due to excessive hydraulic loading from the off-BEP operation.
- **Seal leak** due to excessive axial movement

c) **Inherent Risk Assessment:** in this step, the analysis team proceed with the risk assessment of the consolidated failure modes list, which contains the six failure modes mentioned in the previous two steps. The analysis team has used the risk matrix in Table 6 to assess each failure mode's inherent risk assuming zero-based maintenance. The table also describes each likelihood and consequence level, increasing consistency and reducing the assessment time.

Table 6: Case study risk matrix consequences and likelihood levels description

For the non-financial risk:

Likelihood				Consequences		
No.	Detailed description	Description	Level	Minor	Moderate	Major
				10	100	1000
1	Likely to occur more frequently than mission time (failure mode could happen more than one time during one year)	Likely	0.5	5	50	500
2	Likely to occur less frequently than mission time (failure mode could happen more than one time for five years)	Less likely	0.03	0.3	3	30
3	Unlikely to occur, but possible	unlikely	0.001	0.01	0.1	1

Consequences' levels detailed description

No.	Description	Safety	Environment	Operation
1	Minor	First aid case	Emissions discharges within the unit	System shutdown
2	Moderate	Lost time injury	Emissions discharges within the plant	Unit shutdown
3	Major	Fatality	Emissions discharges outside the plant	Plant shutdown

For the financial risk:

$$\mathit{Financial\ Risk} = (\mathit{repair\ cost} + \mathit{Producation\ loss} + \mathit{other\ losses}) \times \mathit{Likelihood}$$

Using the risk matrix and the provided level descriptions, the analysis team has assessed the inherent risk of the consolidated failure mode list, as indicated in the inherent risk assessment section of Table 7.

4.2.2. The status quo (the warranty agreement maintenance package) analysis

The warranty agreement follows the OEM recommended maintenance package, which includes the following tasks:

- **Daily inspection** to observe all gauges and check any signs of leaks, noise, or vibration. Also, to check the readiness of the standby pump.
- **Monthly inspection** to check lubricant contamination by sample analysis. Also, to check all power/instrument cable glands for tightness and all paint or protective coatings
- **Periodic inspection (six-monthly)** to calibrate the instruments. Also, check foundation bolts for secure attachment, looseness, cracking or general distress.
- **Re-lubrication (six-monthly)** to change the oil at intervals of (4000) operating hours or at least every six months.
- **Internal inspection (three years)** to change the bearings. Also, to check the internal condition of the pump and all ancillary pipework for corrosion/erosion.

The *status quo* scenario is then created by linking each warranty maintenance task to the failure modes it mitigates, as presented in the warranty maintenance package section in Table 7. Then, the analysis team performs the residual risk assessment task considering the package implementation. Also, Table 8 shows the risk reduction factor and value-added indicator calculations for the warranty maintenance package. As per the table, the package's annual cost is $17,107; also, the package's risk reduction factor is (81%), which is the average of the individual tasks risk reduction factor. The package's value-added indicator is (58%), indicating a significant cost-saving opportunity.

Table 7:The case study inherent and residual risk assessment

Inherent Risk Assessment

Failure Mode	Safety			Environment			Operation			NFIR	Financial					FIR $
	L	C	IR	L	C	IR	L	C	IR		L	RC $	PL $	OL $	RC+PL+ OL	
Bearing fatigue	0.03	10	0.3	0.001	10	0.01	0.03	10	0.3	**0.61**	0.001	15,000	1,000	-	16,000	**16**
Bearing seizes	0.03	10	0.3	0.03	10	0.3	0.03	100	3	**3.6**	0.5	15,000	1,000	-	16,000	**8,000**
Casing erosion	0.001	10	0.01	0.03	100	3	0.03	10	0.3	**3.31**	0.03	250,000	5,000	-	255,000	**7,650**
Impeller wear	0.03	10	0.3	0.001	10	0.01	0.5	10	5	**5.31**	0.03	150,000	5,000	-	155,000	**4,650**
Seal leak	0.5	100	50	0.5	10	5	0.03	10	0.3	**55.3**	0.5	20,000	1,000	1,000	22,000	**11,000**
Shaft crack	0.001	10	0.01	0.001	10	0.01	0.001	100	0.1	**0.12**	0.001	200,000	5,000	-	205,000	**205**

Residual Risk Assessment

Failure Mode	Inherent Risk Assessment		Maintenance Task	Task Interval	Interval Unit	Task Cost $	Residual Risk Assessment				
	NFIR	FIR $					SRR	ERR	ORR	NFRR	FRR $
The warranty maintenance package											
Bearing fatigue	**0.61**	**16**	Monthly inspection	1	Month/s	30	0.01	0.01	0.3	**0.32**	**9**
			Re-lubrication	6	Month/s	200	0.01	0.01	0.3		
Bearing seizes	**3.6**	**8,000**	Monthly inspection	1	Month/s	30	0.3	0.3	0.1	**0.7**	**480**
			Re-lubrication	6	Month/s	200	0.3	0.3	0.1		
Casing erosion	**3.31**	**7,650**	Internal inspection	3	Year/s	5,000	0.01	0.1	0.3	**0.41**	**255**
Impeller wear	**5.31**	**4,650**	Daily inspection	1	Day/s	40	0.3	0.01	0.3	**0.61**	**155**
Seal leak	**55.3**	**11,000**	Daily inspection	1	Day/s	40	3	0.3	0.3	**3.6**	**660**
Shaft crack	**0.12**	**205**	Internal inspection	3	Year/s	5,000	0.01	0.01	0.01	**0.03**	**105**
			Periodic inspection	6	Month/s	40	0.01	0.01	0.01		
The In-house maintenance package											
Bearing fatigue	**0.61**	**16**	Oil Analysis	6	Month/s	200	0.01	0.01	0.3	**0.03**	**11**
			Vibration Analysis	1	Month/s	100	0.01	0.01	0.01		
Bearing seizes	**3.6**	**8,000**	Oil Analysis	6	Month/s	200	0.3	0.3	0.1	**0.7**	**16**
			Vibration Analysis	1	Month/s	100	0.3	0.3	0.1		
Casing erosion	**3.31**	**7,650**	Vibration Analysis	1	Month/s	100	0.01	0.1	0.3	**0.41**	**255**
Impeller wear	**5.31**	**4,650**	Operator Rounds	1	Day	20	0.3	0.01	0.01	**0.32**	**155**
			Vibration Analysis	1	Month/s	100	0.3	0.01	0.01		
Seal leak	**55.3**	**11,000**	Operator Rounds	1	Day	20	3	0.01	0.3	**3.31**	**660**
Shaft crack	**0.12**	**205**	Vibration Analysis	1	Month/s	100	0.01	0.01	0.01	**0.03**	**155**
The local provider maintenance package											
Bearing fatigue	**0.61**	**16**	Monthly inspection	1	Month/s	30	0.01	0.01	0.3	**0.32**	**9**
			Re-lubrication	6	Month/s	200	0.01	0.01	0.3		
Bearing seizes	**3.6**	**8,000**	Monthly inspection	1	Month/s	30	0.3	0.3	0.1	**0.7**	**480**
			Re-lubrication	6	Month/s	200	0.3	0.3	0.1	**0.7**	**480**
Casing erosion	**3.31**	**7,650**								**3.31**	**7,650**
Impeller wear	**5.31**	**4,650**	Daily inspection	1	Day/s	15	0.3	0.01	0.3	**0.61**	**155**
Seal leak	**55.3**	**11,000**	Daily inspection	1	Day/s	15	3	0.3	0.3	**3.6**	**660**
Shaft crack	**0.12**	**205**	Periodic inspection	6	Month/s	45	0.01	0.01	0.01	**0.03**	**105**

Table 8: The risk reduction factor and value-added indicator calculations

No.	Task	Task Interval	Interval Unit	Task Cost $	Task annual cost	Failure Mode	Inherent Risk Assessment		Residual Risk Assessment		RRF	VAI
							NFIR	FIR	NFRR	FRR		
The warranty maintenance package												
1	Daily inspection	1	Day/s	40	14,600	Impeller wear	5.31	4,650	0.61	155	93%	2%
						Seal leak	55.3	11,000	3.6	660		
2	Internal inspection	3	Year/s	5,000	1,667	Casing erosion	3.31	7,650	0.41	255	87%	78%
						Shaft crack	0.12	205	0.03	105		
3	Monthly inspection	1	Month/s	30	360	Bearing fatigue	0.61	16	0.32	9	76%	95%
						Bearing seizes	3.6	8,000	0.7	480		
4	Periodic inspection	6	Month/s	40	80	Shaft crack	0.12	205	0.03	105	75%	20%
5	Re-lubrication	6	Month/s	200	400	Bearing fatigue	0.61	16	0.32	10	76%	95%
						Bearing seizes	3.6	8,000	0.7	480		
The warranty maintenance package annual cost					**17,107**	**The warranty maintenance package indicators**					**81%**	**58%**
The in-house maintenance package												
1	Oil Analysis	6	Month/s	200	400	Bearing fatigue	1	16	0.3	11	76%	95%
						Bearing seizes	4	8,000	0.7	16		
2	Operator Rounds	1	Day/s	20	7,300	Impeller wear	5	4,650	0.3	155	94%	51%
						Seal leak	55	11,000	3.3	660		
3	Vibration Analysis	1	Month/s	100	1,200	Bearing fatigue	1	16	0.0	12	83%	85%
						Bearing seizes	4	8,000	0.7	16		
						Casing erosion	3	7,650	0.3	155		
						Shaft crack	0.1	205	0.0	155		
The in-house maintenance package annual cost					**8,900**	**The in-house maintenance package indicators**					**84%**	**77%**
The local provider maintenance package												
1	Daily inspection	1	Day/s	15	5,475	Impeller wear	5.31	4,650	0.61	155	93%	63%
						Seal leak	55.3	11,000	3.6	660		
2	Monthly inspection	1	Month/s	30	360	Bearing fatigue	0.61	16	0.32	9	76%	95%
						Bearing seizes	3.6	8,000	0.7	480		
3	Periodic inspection	6	Month/s	45	540	Shaft crack	0.12	205	0.03	105	75%	10%
4	Re-lubrication	6	Month/s	200	2,400	Bearing fatigue	0.61	16	0.32	10	76%	95%
						Bearing seizes	3.6	8,000	0.7	480		
The local provider maintenance package annual cost					**8,775**	**The local provider maintenance package indicators**					**80%**	**66%**

4.2.3. The in-house maintenance package analysis

As depicted in Figure 2, the analysis team proposes an alternative maintenance package for the post-warranty period based on their experience and industry best practices. The following package has been proposed:

- **Operator Rounds (Daily)** this task focuses on seals, packing, and gaskets to detect visible leaks of oil and water, unusual noises, loose or missing hardware, temperature, pressure, and other parameters that are out of specification.
- **Vibration Analysis (monthly)** this task addresses sources of vibration in rotating parts and flow noise such as cavitation. The task includes analysing the readings and looking for misalignment and unusual spectrums that may indicate problems. Also, visual inspection for signs of leaking lubricant loose fasteners. Besides, listening for unusual noises that may indicate coupling problems
- **Oil Analysis (six-monthly)** This task focuses on detecting degraded oil because of its bad effects on other components. The task includes analysing the oil for wear particles, contaminants, water, and lubricity qualities. Also, performing a visual check for signs of oil leakage.

The in-house maintenance scenario is then developed by linking each maintenance task to the failure modes it mitigates, as depicted in the In-house maintenance package section in Table 7. Then, the analysis team performs the residual risk assessment task considering the package implementation. Also, Table 8 shows an annual cost of $8,900 for the proposed in-house maintenance package and a value-added indicator of 77% and a high-risk reduction factor of 84%.

4.2.4. The local provider maintenance package analysis

The maintenance package offered by the local provider provides the same warranty agreement tasks except for the three-yearly internal inspection task; the package comes at a lower cost and includes:

- **Daily inspection** to observe all gauges and check any signs of leaks, noise, or vibration. Also, to check the readiness of the standby pump.
- **Monthly inspection** to check lubricant contamination by sample analysis. Also, to check all power/instrument cable glands for tightness and all paint or protective coatings
- **Periodic inspection (six-monthly)** to calibrate the instruments. Also, check foundation bolts for secure attachment, looseness, cracking, or general distress.
- **Re-lubrication (six-monthly)** to change the oil at (4000) operating hours or at least every six months.

The scenario is then created by linking each maintenance task to the failure modes it mitigates, as presented in the local provider maintenance package section in Table 7. Then, the analysis team performs the residual risk assessment task considering the package implementation. Additionally, Table 8 shows the risk reduction factor and value-added indicator calculations for the local provider maintenance package. As per the table, the package's annual cost is $8,775; also, the package's risk reduction factor is (80%), which is the average of the individual tasks risk reduction factor. The package's value-added indicator is (66%), which indicates a significant opportunity for cost-saving.

Finally, Figure 7 illustrates a high-level comparison between the status quo scenario, the in-house maintenance scenario and the local provider maintenance scenario in terms of risk reduction. The figure shows the links between the failure modes and the tasks. Also, each failure mode is coloured according to the risk level, where high risk is red and low risk is green.

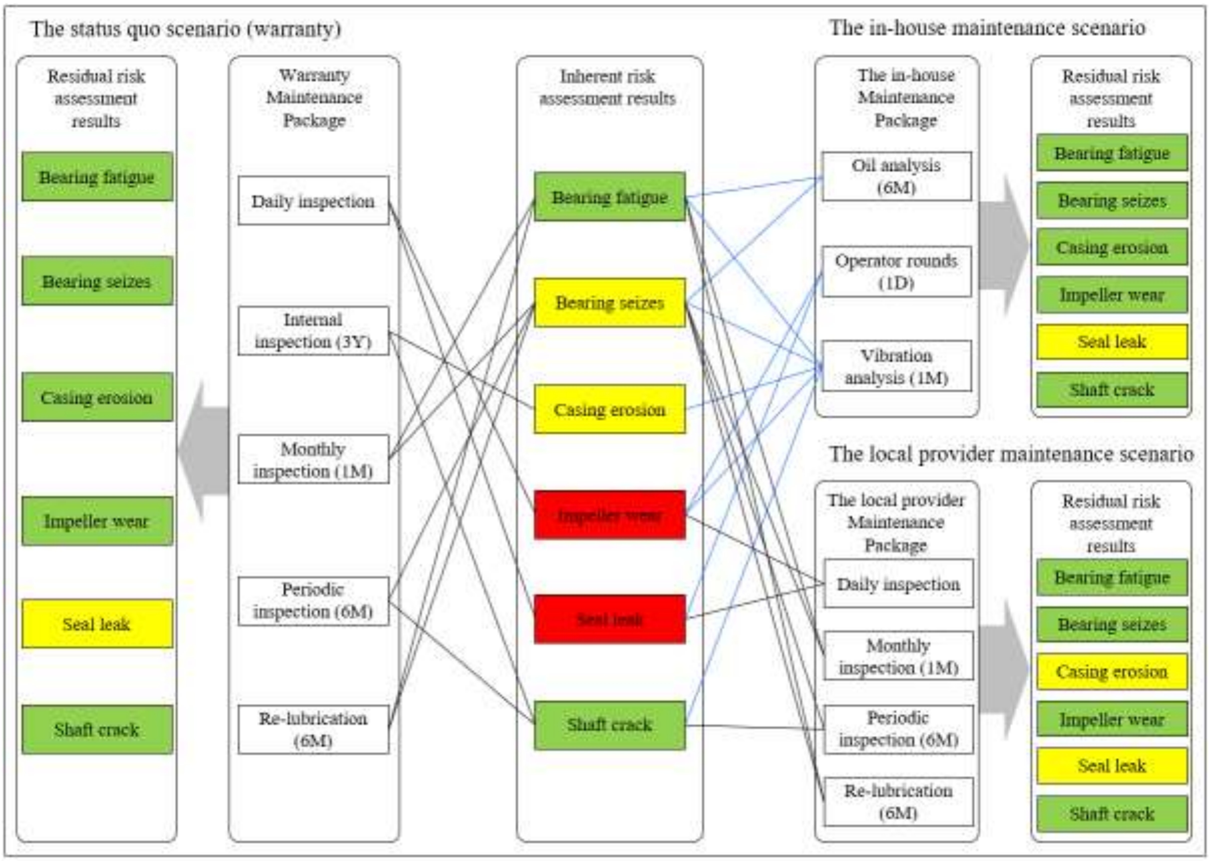


Figure 7: Case study status quo vs. in-house vs. local provider maintenance packages

4.2.5. Final decision using analytical hierarchy process (AHP)

As the selection of equipment optimum maintenance strategy is a multiple criteria decision-making. SPP uses AHP to calculate the criteria weight for package annual cost (PAC), package risk reduction factor (PRRF) and package value-added indicator (PVAI), as depicted in Figure 8.

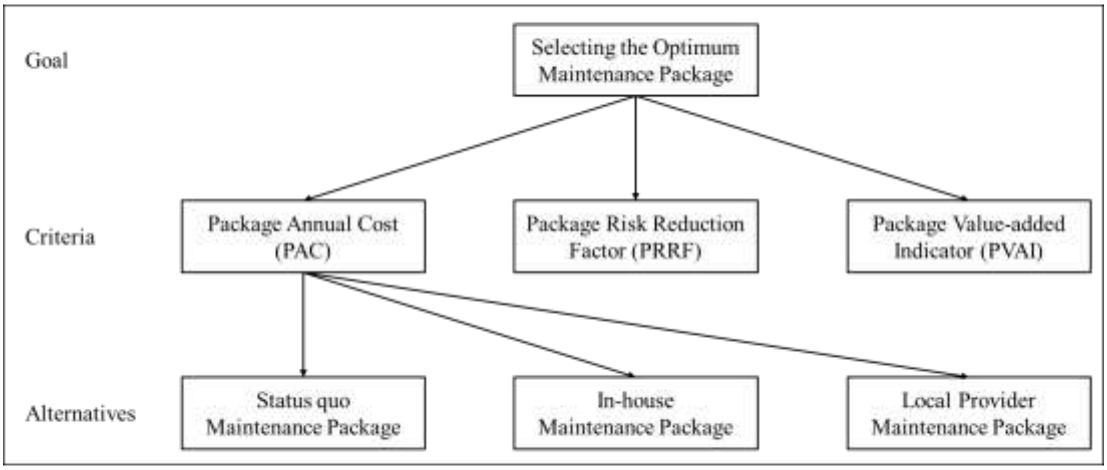


Figure 8: Hierarchical structure

Then, Table 9 shows the pair-wise comparison matrix that uses a relative importance scale of various attributes with respect to the goal to be used in the pair-wise comparison, where:

- 1 : Equal importance
- 3 : Moderate importance
- 5 : Strong importance
- 1/3 , 1/5: Values of inverse comparison

For instance, the analysis team considers PAC as strong important than PVAI and moderate importance than PRRF. Also, the table indicates the calculated PAC, PRRF and PVAI values for each maintenance package. Then, the calculated values are normalised, where for PRRF and PVAI, the best value is the highest, so the normalisation is done by dividing by the highest value. As the lowest value is better for the PAC, normalisation is performed against the lowest value.

Table 9: Pair-wise comparison matrix and Normalised values calculations for PAC, PRRF and PVAI

Pair-wise comparison matrix

	PAC	PRRF	PVAI	Criteria Weight
PAC	1	3	5	0.637
PRRF	1/3 = 0.333	1	3	0.258
PVAI	1/5 = 0.200	1/3 = 0.333	1	0.105
Maximum Eigen Value =3.03851, C.I.=0.0192555, Weights (Eigen Vector)				

Normalised values calculations for PAC, PRRF and PVAI

Maintenance Package	PAC	PRRF	PVAI	Normalised values		
				8,775/PAC	PRRF/0.840	PVAI/0.770
Status quo (warranty)	17,107	0.810	0.580	0.513	0.964	0.753
In-house	8,900	0.840	0.770	0.986	1	1
Local Provider	8,775	0.800	0.660	1	0.952	0.857
	8,775	0.840	0.770			

Finally, the decision matrix for selecting the post-warranty maintenance package using AHP is developed as:

$$
\begin{array}{cccccc}
\text{PAC}\qquad\text{PRRF}\qquad\text{PVAI} & & \text{Criteria weight} & & \text{Priority number} & \\
\begin{vmatrix} 0.513 & 0.964 & 0.753 \\ 0.986 & 1 & 1 \\ 1 & 0.952 & 0.857 \end{vmatrix} & \times & \begin{vmatrix} 0.637 \\ 0.258 \\ 0.105 \end{vmatrix} & = & \begin{vmatrix} 0.655 \\ 0.991 \\ 0.973 \end{vmatrix} & \begin{matrix} Status\ quo \\ In - house \\ Local\ Provvider \end{matrix}
\end{array}
$$

The selected maintenance package is the one with the highest priority number, which is the in-house maintenance package. Although this package did not achieve the lowest score in relation to PAC, it got the top score for PRRF and PVAI.

Risk Profile Comparison

Also, Figure 9 shows a more mitigated non-financial risk profile by the in-house maintenance package than the local provider maintenance package and the warranty agreement. Moreover, it shows a more mitigated financial risk profile by the in-house maintenance package compared with the local provider maintenance package.

	Bearing fatigue	Bearing seizes	Casing erosion	Impeller wear	Seal leak	Shaft crack
Inherent Risk	0.61	3.6	3.31	5.31	55.3	0.12
Warranty Agreement	0.32	0.7	0.41	0.61	3.6	0.03
In-house Maintenance	0.03	0.7	0.41	0.32	3.31	0.03
Local Service Provider	0.32	0.7	3.31	0.61	3.6	0.03

	Bearing fatigue	Bearing seizes	Casing erosion	Impeller wear	Seal leak	Shaft crack
Inherent Risk	16	8,000	7,650	4,650	11,000	205
Warranty Agreement	9	480	255	155	660	105
In-house Maintenance	11	16	255	155	660	155
Local Service Provider	9	480	7650	155	660	105

Figure 9: Packages non-financial risk profile comparison

Figure 10 summarises SPP outcomes as it shows VAI, RRF and PAC for each maintenance package. As in the figure, the in-house maintenance package has the highest VAI and RRF, while the local provider maintenance package has the lowest PAC. On the other side, the status quo maintenance package has the lowest VAI and the highest PAC. Hence SPP recommends implementing the in-house maintenance package as per the analytical hierarchy process and the developed risk profiles.

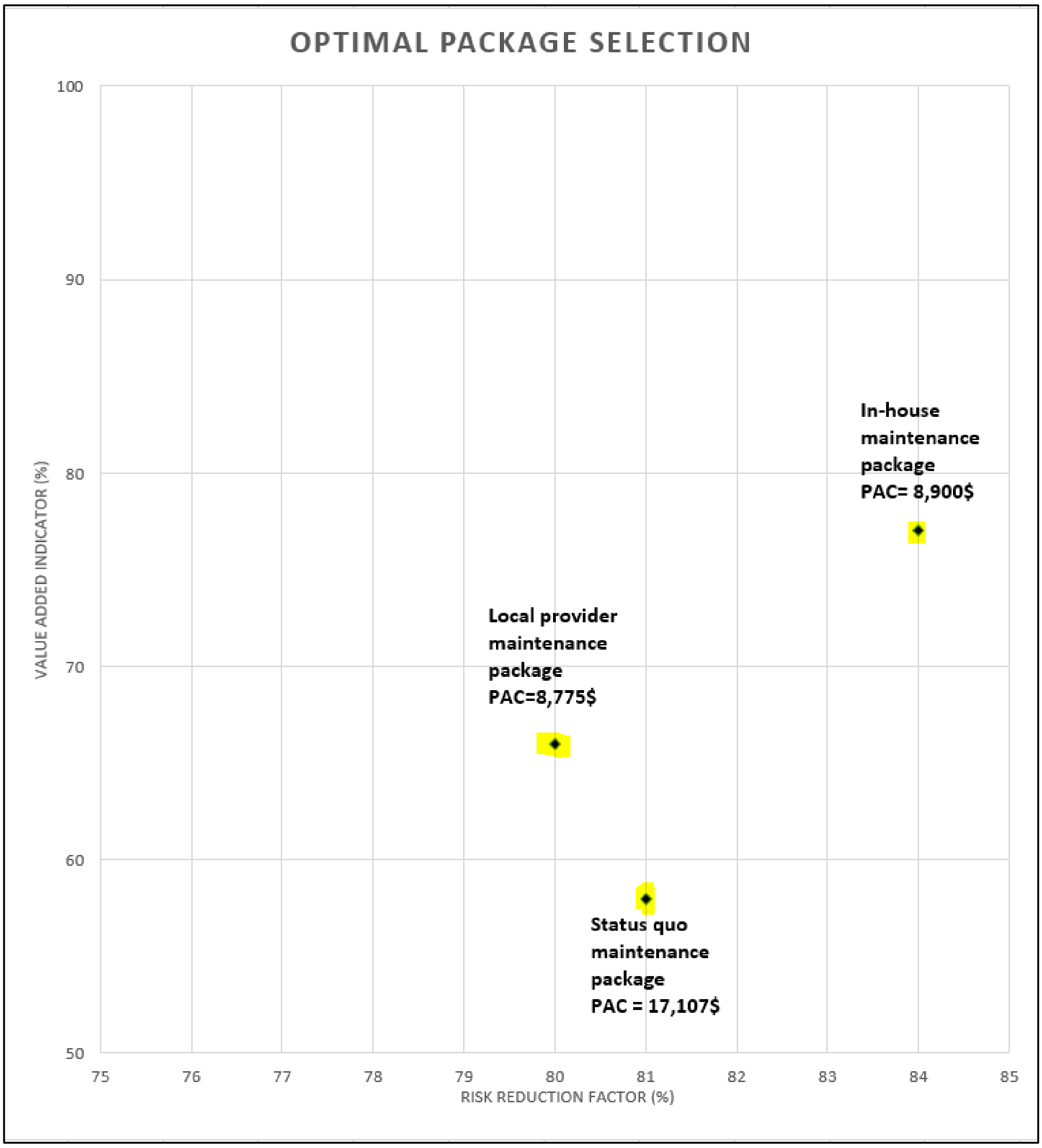


Figure 10: Post-warranty maintenance package selection

5. Conclusion

This paper investigates a collaborative framework that enables asset engineering and management teams to decide whether to renew an existing warranty contract, select a different maintenance contractor, or move to in-house maintenance, with a focus on reducing the financial risk of production disruption during the transition to the post-warranty period.

The proposed SPP extends the post-warranty maintenance research as it allows the comparison of multiple maintenance packages considering package cost and failure risk, which VAI and RRF reflect, respectively. Also, the SPP employs the AHP to assist asset owners in setting their priorities according to the organisation's risk appetite and cutback pressure before deciding the post-warranty maintenance strategy for the cooling water pump based on the suggested maintenance packages VAI, RRF and cost, as the case study shows; and to further facilitate the selection process, the SPP gives the asset owner more visibility of the inherent risk, financial and non-financial risk profiles of the proposed packages, which provide the basis of what-if scenarios to enable informed decision-making and cost-cutting, as perceived by the cooling water pump stakeholders.

In this research, we consider the maintenance strategy selection from an asset owner perspective, this can be further extended through the application of the SPP process from a warrantor and maintenance service provider viewpoint to tailor, offer, justify and negotiate different warranty extension packages that suit the different operating contexts; in line with the recent trend in warranty management in which the warrantors are offering adaptable extended warranty options [50, p. 248]. Another interesting area for future research would be to study a dynamic (evergreen) decision process that checks the maintenance package and retunes it at given (trigger) time points as new data arises. Also, implementing the SPP as a quality gate to justify and evaluate new maintenance strategies developed by RCM or FMEA could be an exciting area to investigate.

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article.

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