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The business case for condition-based maintenance: A hybrid (non-) financial approach

W.W. Tiddens & T. Tinga
University of Twente, Enschede, The Netherlands
Netherlands Defence Academy, Den Helder, The Netherlands

A.J.J. Braaksma
University of Twente, Enschede, The Netherlands

O. Brouwer
Netherlands Aerospace Centre, Amsterdam, The Netherlands

ABSTRACT: Although developing business cases is key for evaluating project success, the costs and benefits of Condition-Based Maintenance (CBM) implementations are often not explicitly defined and evaluated. Using the design science methodology, we developed a hybrid business case approach to help managers evaluate and justify implementing CBM. We conclude that depending on the innovativeness (for the organization) of the applied technique, the business case should have a different goal orientation and be composed of different support elements. We use the proposed hybrid business case approach in an in-depth single case study that focusses on developing engine condition trend monitoring for a military transport aircraft. The case study explores differences in applying innovative maintenance techniques (exploration) or applying well-known techniques (exploitation). Using a combination of non-financial (strategic multi-criteria analysis) and financial elements (using Monte Carlo simulation), we compared the investment in CBM with both fixed-interval preventive maintenance and corrective maintenance.

1 INTRODUCTION

Maintenance techniques such as condition monitoring, enable the application of maintenance policies like Condition-Based Maintenance (CBM). CBM is widely applied in industry, within other domains, for example the military, a comparable strategy is used: Prognostics and Health Management (PHM).

CBM uses condition monitoring techniques such as vibration monitoring and oil analysis to determine the asset's current condition. Based on this condition, maintenance actions can be recommended. Moreover, maintenance decision making is supported by taking the current, but preferably also the future state of capital assets into account. The goal of these types of maintenance strategies is to help asset owners, Original Equipment Manufacturers (OEMs) and service providers to increase equipment availability and decrease maintenance costs of their assets.

However, although developing business cases is key for evaluating project success (Fortune & White, 2006), the—monetary—costs and benefits of CBM implementations are often not explicitly defined and evaluated in practice (Tiddens et al., 2015).

Moreover, the uncertainty of these costs and benefits depends on the type and innovativeness of the applied technique while in practice the different techniques are often considered as being similar. As also case studies conducted by the authors show, only few practitioners have effectively applied maintenance techniques. Moreover, not all industrial equipment benefits from these techniques; almost 30% of industrial equipment does not benefit from CBM (Hashemian & Bean, 2011). Therefore, it is important to evaluate the investment in CBM in advance. Often, the full potential of CBM techniques is not achieved and a costly trial-and-error approach is followed in the implementation of CBM (Tiddens et al., 2015). Finally, uncertainties in costs and benefits of developing innovative CBM approaches stress the need for solid business cases.

Current methods for making the business case for CBM often require many input parameters, which are regarded as 'knowns', and they focus on the exact calculation of financial parameters. However, in practise this data is unavailable or very difficult to acquire. Moreover, the benefits of CBM implementations are difficult to quantify (Bo et al., 2010). In determining these benefits, many factors play a role: the current maintenance plan, safety boundaries, the logistics support system and the technical features of the prognostic technique (Bo et al., 2010). But also the prognostic technique's quality and accuracy, its development costs and the asset's failure distribution. Finally, intangible benefits (e.g. safety improvements or reputation) play a role, but are hard to quantify.

1.1 *Research method and outline of the paper*

This paper presents a hybrid business case approach to help managers evaluate and justify a planned development of CBM.

The design science methodology (Holmström et al., 2009) has been used to guide the design of this investment evaluation. Therefore, first, related research and findings from case studies conducted by the authors provide the design criteria. Next, the initial design is elaborated on and evaluated using the single-case study (cf. Ketokivi & Choi, 2014). We conclude that depending on the uncertainty of the applied technique, the hybrid business case should have a different goal orientation and different support elements. Therefore, we propose a method to evaluate the investment in CBM in section 3 based on the identified design principles and criteria from section 2. In section 4, we apply the proposed method to a case study at the Royal Netherlands Air Force. Finally, conclusions are given in section 5.

2 EVALUATING THE INVESTMENT IN CBM: A REVIEW OF METHODS

To be able to understand how the business case for CBM should be constructed, we start with reviewing the current literature on methods for investment evaluations. First, we will evaluate the type of models available. And after that, we will discuss financial and non-financial models to specifically evaluate investments in CBM.

2.1 *Methods for investment evaluation*

Renkema & Berghout (1997) reviewed various methods to evaluate investments in Information Systems (IS). Also within the IS domain, it is difficult to formally justify investments, because reliable estimates of costs and benefits are not always available (Remenyi & Sherwood-Smith, 2012). In their review, Renkema & Berghout (1997) distinguish four approaches:

i. the financial approach: these methods focus on the incoming and outgoing cash flow as a result of the investment, e.g. Return On Investment (ROI).

ii. the multi-criteria approach: these methods score the different alternatives on several pre-set criteria. These can be financial as well as non-financial consequences.

iii. the ratio approach: this approach evaluates the ratio of the investment costs against for example the total turnover. These are not necessarily only financial figures, it can for example also relate to the number of employees.

iv. the portfolio approach: this approach considers a specific product mix. In the project portfolio the combination of projects or investments are plotted against several evaluation criteria. In the portfolio approach of Bedell (1984), a trade-off has to be found between importance and quality of the project. Three questions that are raised in this method (reformulated to the application of CBM evaluations): (*i*) should the organization invest in CBM methods?; (*ii*) in which activities should the organization invest?; (*iii*) which techniques for CBM should be developed?

Business cases can be constructed on macro, meso and micro levels (Remenyi & Sherwood-Smith, 2012). A macro model employs a general concept on a high level. It contextualises the problem or opportunity and presents a conceptual picture of a suggested solution. A macro approach can be followed when there is little specific (i.e. failure) data to assess the effects of the CBM approach. When more data is available, the business case can be constructed on a deeper level. A meso level model adds more detail. It expresses generalities of the dimensions of the problem and proposed solution on an intermediate level. A micro level model helps to understand the detailed impact of the proposed solution. Remenyi & Sherwood-Smith (2012) note that although all models are simplifications of the reality by nature, the simpler the model, the more meaningful they may be.

2.2 *Financial metrics applied to CBM justification*

Traditional investment evaluation criteria can be applied to evaluate investments in CBM. Metrics such as the Return On Investment (ROI) and Net Present Value (NPV) focus on projecting the (future) costs and benefits of a CBM policy. The return on investment metric can be calculated as the return minus the investment, divided by the total investment. Feldman et al. (2009) show the simplest formulation (Equation 1) of the return on investment applied to the evaluation of prognostic techniques. They compare the costs of CBM (C_{CBM}) to the costs of unscheduled maintenance

(C_{UM}). C_{UM} and C_{CBM} are lifecycle costs. C_{CBM} includes all investments in CBM (I_{CBM}), all the changes to the life-cycle costs, and the costs of the undetected failures. I_{CBM} consists of the costs of the required infrastructure added to the recurring and non-recurring costs.

$$ROI = \frac{C_{UM} - \left(C_{CBM} - I_{CBM}\right)}{I_{CBM}} - 1 \quad (1)$$

The Net Present Value is an important capital budgeting model that considers discounted cash flows; the metric considers the present value of both benefits and costs (i is the discount rate). Equation 2 shows the calculation of the NPV (Myers, 1984). Regular NPV calculations focus on a certain return (R_t), an incoming monetary flow (as for example in the ROI method). However, in the case of CBM, the 'benefits' can only be found in cost savings resulting from cost reductions (less repairs and replacements) and cost avoidances (avoiding failures). Therefore, in the case of a CBM implementation, R_t should be seen as the cost avoidance (or conversely an increase in costs) that is achieved at time t. This is the difference in the yearly lifecycle costs of an Unscheduled Maintenance (UM) or Preventive Maintenance (PM) approach compared to a CBM approach. C is the cost of the project at $t = 0$.

$$NPV(i,N) = \sum_{t=0}^{N}\left(\frac{R_t}{(1+i)^t}\right) - C \quad (2)$$

2.3 *Financial approaches to assess the investment in CBM*

A number of methods to evaluate the financial investments in prognostic techniques are discussed in the academic literature.

In the field of maintenance optimisation, extensive work has been conducted to determine the optimal balance between the costs and benefits of maintenance (for an overview see: Dekker, 1996). The state of the art in simulation based optimisation has been reviewed by Alrabghi & Tiwari (2015). These simulation based approaches have a large potential and growing interest amongst researchers in optimising maintenance systems (Sharma et al., 2011). Using these approaches, a business case for CBM could be constructed. However, these approaches often require many input variables which make them hard to apply in practice. Reliability data can be sparsely available and sensored, therefore, additional information from expert judgement is important (Marquez et al., 2007).

Sandborn & Wilkinson (2007) present a discrete event simulation model that results in a methodology to establish a business case for PHM. Therefore, they determine the optimal prognostic distance and safety margin (i.e. how far into the future can a failure be predicted) for various PHM approaches. Short prognostic distances increase the probability of missing failures, while long prognostic distances may be costly to achieve. High safety margins result in throwing away remaining useful life. In their model, Sandborn & Wilkinson (2007) include single and multiple socket systems where the Line Replaceable Units (LRU's) that make up a system can be subject to different PHM approaches (or no PHM structure at all). Using Monte Carlo simulations, they compare unscheduled and fixed-interval maintenance policies with the PHM approaches.

2.4 *Non-financial approaches to assess the investment in CBM*

A financial evaluation of an investment in CBM looks only at the impact on the internal processes of the maintenance function. However, managers want a balanced presentation of both financial and operational measures (Kaplan & Norton, 2005, p.172). Moreover, an evaluation that only considers financial criteria might fail to account for the impact on functions external to the maintenance function such as production, logistics, customers, employees and organizational goals (Kumar et al., 2013). Finally, a purely financial evaluation neglects the skills and competencies that companies are trying to master (Kaplan & Norton, 2005). Such a balanced evaluation can be made with the balanced scorecard.

Alsyouf (2006) presents an extended balanced scorecard which can be applied to maintenance. Alsyouf (2006) demonstrates with cause and effect relationships how maintenance can contribute to the firm's overall success. Therefore, he describes six perspectives. These are (influencing one another from bottom to top): (*i*) innovation and growth; (*ii*) maintenance; (*iii*) production; (*iv*) customer; (*v*) society; and (*vi*) financial.

In conclusion, the non-financial approaches are useful in finding out whether a CBM approach is of strategic interest to the company. These however lack a detailed financial calculation that incorporates the uncertainty of developing CBM. The discussed financial approaches incorporate uncertainty and are helpful in creating a detailed business case. However, sufficient data is not always available for such an evaluation, specifically for innovative approaches.

A combination that includes the specific uncertainties associated with introducing CBM and the strategic considerations of the firm is missing.

3 PROPOSED APPROACH TO EVALUATE THE INVESTMENT IN CBM

Following the design science methodology (Holmström et al., 2009), after discussing literature on (non-) financial evaluation methods, the next step is to formulate the design principles for the initial design of the business case approach.

First design principle: exploring or exploiting.
Tidd & Bessant (2009) argue that organizations should organize and manage various innovation types differently. *Exploitation* of an innovation happens when adaptive and incremental development takes place. *Exploration* happens when new territory is explored and the frontiers of what is known are pushed.

The application of CBM sometimes seems to be treated as incremental, as several techniques for CBM, like vibration or oil analysis, can be considered to be proven technology. However, as also shown in Tiddens et al. (2015), a trial-and-error process is often followed in the implementation of CBM. As many contextual factors such as the maturity of the organization, extisting knowledge and experience within a company play a role, CBM implementations should often be treated as local innovations. This means that where a proven technique (e.g. vibration monitoring) can be an *exploitation* of CBM for firm *A*, firm *B* that is not experienced in applying this technique might have to approach this as an *exploration* of CBM. Therefore, the approach to justify and evaluate the investment should also depend on the context in which a technology such as CBM is applied, rather than solely considering the degree of newness of a technology.

Second design principle: hybrid-approach.
Many of the reviewed justification methods (section 2) follow the financial approach (cf. Renkema & Berghout, 1997) and can be characterized as micro-models (cf. Remenyi & Sherwood-Smith, 2012). The reviewed non-financial approaches take a more strategic (macro) non-financial approach. However, these models exclude uncertainties of the inputs. For example, Monte Carlo analyses can help to include these to give a better picture of the sensitivity of the business case result.

We therefore argue that a hybrid approach, consisting of a financial and non-financial evaluation should be followed in the evaluation of CBM investments. Depending on the uncertainty and innovativeness (for the specific firm), the business case should have a different goal orientation and different support elements. As Renkema & Berghout (1997) noted, four approaches can be followed (financial, multi-criteria, portfolio, and ratio approach). Myers (1984) argues that discounted cash flow methods (i.e. NPV) can be safely applied to cash cows (relative safe businesses / investments). However, these methods are less helpful in valuing investments that have substantial growth opportunities and in assessing strategic value (Myers, 1984, p.135).

Third design principle: flexible goal orientation.
The hybrid approach should offer the possibility to switch between a strategic non-financial assessment on a macro level or a detailed financial modelling on a micro level as suggested by (Remenyi & Sherwood-Smith, 2012). This means that for *exploitation* of CBM techniques, the goal orientation is to evaluate the financial contribution to the firm. Therefore, a detailed financial evaluation on a micro level using the Monte Carlo approach of Sandborn & Wilkinson (2007) can be made. The business case can then be supported with traditional financial elements (i.e. ROI, NPV).

For *exploration* cases, the goal orientation should be to assess the strategic impacts of the CBM approach on the firm on a high (macro) level. The business case can then be supported with non-financial methods such as a multi-criteria analysis using the extended balanced scorecard of Alsyouf (2006). Also a portfolio approach could be applied in this situation. By using the considerations of Bedell (1984), it can be evaluated whether the organizations should introduce CBM and what activities and techniques should be employed.

Note that in practical cases often a combination of *exploitation* and *exploration* is found. Although some proven technologies may be adopted, the overall CBM strategy and implementation is typically an exploratory process for any company. That once more motivates why a hybrid approach is required.

The proposed hybrid approach (Figure 1) starts with analysing whether the CBM introduction can be categorized as merely *exploration* or *exploitation*. This directs the goal orientation of the business case.

For *exploration* cases, a non-financial evaluation has to be made. Where possible (i.e. this can only be done if sufficient information on the CBM approach is available), this evaluation has to be complemented (dotted line) with a financial evaluation to assess whether it is expected that the CBM introduction can reduce costs.

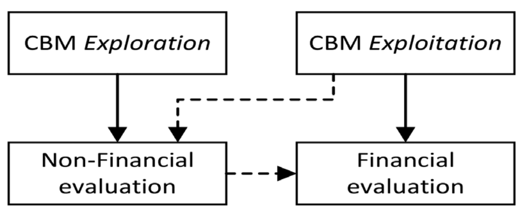

Figure 1. Proposed hybrid business case approach. Following the dashed lines is recommended but optional.

For *exploitation* cases, it is optional (dotted line) to start with a non-financial evaluation to assess whether, strategically, it is beneficial to invest in CBM techniques. After this, a financial evaluation should be conducted to assess the financial consequences.

3.1 *Exploration of CBM: Non-financial evaluation*

As was mentioned before, the exploration part of CBM implementations must be tackled with a high level non-financial approach to assess the strategic impacts. Depending on the objectives and ambition of the firm, several routes can be followed.

First, when the firm is orienting on investing in methods to improve their maintenance process, a ratio approach can be used to dedicate a certain percentage of the maintenance budget to the development of techniques that enable CBM.

Second, if the firm is orienting on different types of techniques to develop, a portfolio approach can be adopted. Then, the firm can decide to invest primarily in *exploitations* for example, but also investigate the opportunities of *explorations*.

For the latter, a straightforward financial business case is often not possible because the uncertainty of development is high. Financial approaches encourage short-termism while innovations (*explorations*) are typically long term. Therefore, it can be difficult to estimate the benefits. In that case, a more 'innovation management' approach should be followed to assess the impact of the introduction of the CBM technique to the firm. Therefore, a multi-criteria approach can be followed. In this multi-criteria analysis, the factors of the extended balance scorecard of Alsyouf (2006) can be used to assess whether CBM contributes to the firm's success

3.2 *Exploitation of CBM: Financial evaluation*

As strategic analyses are also subject to random error (Myers, 1984), the proposed hybrid approach includes an evaluation of the monetary cost benefits using discrete event simulation. Therefore, an Excel-based Monte Carlo simulation model has been developed using the logic presented by Sandborn & Wilkinson (2007). With this model, failures can be sampled during a given lifecycle of the asset. A comparison of the lifecycle costs, average number of failures and replacements is made between CBM, fixed-interval preventive maintenance and unscheduled maintenance. Both current as calculated (optimal) PM intervals can be selected for comparison.

As smart managers do not accept positive (or negative) NPVs unless they can explain them (Myers, 1984, p.130), the model was simplified by reducing the number of required inputs. Moreover, as data can be censored and sparse (Marquez et al., 2007), the inputs can be obtained from only expert sessions.

The model consists of three modules, being an input, processing, and output module. The input module consists of parameters concerning failure distributions, the prognostic distance, and economic parameters such as (non-) recurring costs. The processing module calculates the outputs using equation 1 and 2. The discrete event simulation works as follows: every simulation trial equals one lifecycle of the fleet of assets. For UM: a simulated failure means asset failure. For PM: for every simulated failure it is checked whether the simulated failure occurs before or after the PM action. In the former case, the asset fails. For the latter, only a PM action takes place at the predefined interval. For CBM: the simulated failure is compared to a sample from the PHM distribution. This distribution shows the probability that the PHM technique 'sees the failure coming' (for further reading, see: Sandborn & Wilkinson, 2007). If the sample of the PHM distribution is smaller than the sample from the failure distribution: a PM action takes place. Otherwise, this leads to an asset failure.

Finally, the output module provides an overview of the economic impact by displaying life cycle costs, net present value, and return on investment.

4 EVALUATING THE INVESTMENT IN CBM FOR THE ENGINES OF THE C130 HERCULES OF THE ROYAL NETHERLANDS AIR FORCE: A CASE STUDY

An in-depth single case study (Yin, 2013) at the Royal Netherlands Airforce is conducted to evaluate the application of the business case approach.

The the Royal Netherlands Air Force (RNLAF) wants to explore the possibilities of conducting more condition-based maintenance activities.

This originates from declining budgets and the perception that the current fixed-interval maintenance policy is too conservative. This is supported by evidence from an ally, having flown many more hours before a failure occurred.

However, as the engines are critical for safe operation of the aircraft, there is a need to substantiate an extension of the overhaul interval. Next to that, safe operation after a potential extension also has to be proven towards the Military Aviation Authorities (MLA). Therefore, together with the Netherlands Aerospace Centre (NLR), the RNLAF has started a pilot project to investigate both the technical and economic feasibility of a CBM program for the engines of the C130 Hercules fleet.

The C130 Hercules (in service since 1994) is an aircraft primarily used for transportation purposes. The whole fleet consists of four aircraft, each driven by four T-56 turboprop engines. To account for long overhaul periods, a number of spare engines are permanently on stock. Currently, the RNLAF applies a fixed-interval planned maintenance policy, based on flight hours. Due to confidentiality, exact numbers cannot be provided. However, it can be noted that the overhaul interval is conservative due to safety regulations and the high costs of failures.

4.1 *Engine condition trend monitoring*

During normal operation, turboprop engines can produce rated power for extended periods of time. Under specific flight conditions, engine operating parameters such as compressor speeds, interturbine temperature and fuel flow for individual engines are predictable (Guimarães, 2015). Hereby, deterioration of gas path components can be detected at an early stage by comparing the actual (measured) parameters to a calculated baseline.

Engine Condition Trend Monitoring (ECTM) is the process of using these measured characteristics during specified flight conditions (i.e. altitude, airspeed, outside air temperatures) and comparing these to predicted values to provide confirmation of engine gas path efficiency and predict maintenance needs based on this data (Guimarães, 2015).

4.2 *Non-financial evaluation of ECTM*

Although ECTM is an established approach to monitor the performance of Hercules engines (Glenny, 1982), application of such technologies and approaches is new for the C130 fleet of the RNLAF. Moreover, due to the varying military flight profiles, measuring the specified flight conditions for ECTM is more difficult than in civil settings. In military settings, the flight profiles are more dynamic (i.e. more flight level variance, low level flight operations, manoeuvres, etc.). Therefore, as the uncertainty of implementing ECTM is high, the new setting requires a more 'innovation management' approach.

To assess the strategic impacts of the introduction of the CBM approach using ECTM at the RNLAF, we conducted a multi-criteria analysis using the six perspectives of Alsyouf (2006), see Table 1. Below we will elaborate on the contribution of the three compared maintenance strategies to the overall success of the RNLAF.

i. innovation and growth: An—for the RNLAF—innovative maintenance policy (ECTM) can be implemented. Improvement of the maintenance organization is important to increase effectiveness and decrease costs, which is necessary due to budget cuts. By investing in relevant and promising maintenance techniques, competences and skills both within as outside (i.e. a research centre as the NLR) can be developed. This can help to improve the effectiveness of the maintenance organization. The impact of this development is therefore rated considerably higher (value 4 in Table 1) than the traditional UM and PM.

ii. maintenance: The CBM introduction can help to reduce the non-utilized remaining life of the engines while complying to safety regulations and standard. However, it is not as easily plannable as fixed-interval PM activities, which can be problematic due to the long repair times of the engines. However, CBM can decrease the load on the maintenance organization by increasing the time between overhauls. We therefore scored PM and CBM equally. UM scores low because it can create high variances in the maintenance organization's work load and many unplanned failures can occur.

iii. The production perspective looks at how the overall operational effectiveness of the RNLAF can be maximised. For the operational units that use the aircraft, safe and reliable operation of the aircraft is key. Therefore, PM and CBM can be scored equally as they both assure reliable operation. Although a longer mean time between overhauls, possible with a CBM approach might improve the availability, we scored PM and CBM equally.

iv. customer: The RNLAF services the government of the Netherlands and their allies. In this respect, improvements in the effectiveness and lower costs are important. We therefore scored the CBM approach higher.

v. society: The defence organization serves the interests of society. Therefore, a reduction in the operating costs and improvements in the operational availability are of interest to the

Table 1. Results of the multi-criteria analysis to assess the (positive) impact of UM, PM and CBM on the non-financial perspectives (1 = low, 5 = high).

Perspective	UM	PM	CBM
(i) innovation and growth	1	2	4
(ii) maintenance	1	3	3
(iii) production	1	3	3
(iv) customer	1	4	5
(v) society	1	4	5
(vi) financial	1	3	3
Total	6	19	23

society. Note: in this case customer and society are more or less the same.

vi. Finally, on the financial perspective, ECTM can help to prevent costs associated with unplanned failures and damages and helps to prevent spoiling remaining useful life by only conducting maintenance when required. A downside of the introduction of ECTM is the substantial capital investment that is required for the development.

The non-financial evaluation has helped to get insight in the contribution that CBM can have to the RNLAF. The highest total score of CBM in the multi-criteria analysis shows that for the RNLAF, it is interesting to conduct a financial evaluation of the introduction of ECTM. As the criticality of the engines and the associated maintenance costs are high, CBM is favourable on a number of perspectives.

Recent budget cuts on the defence department stress the need for innovations that have potential to decrease costs. In other environments, stable fixed-interval policies might be preferable when for example maintenance activities are clustered or factory stops are planned in advance. Further, the introduction of ECTM requires a substantial capital investment, which makes it (from a financial perspective) not directly favourable over PM. It is therefore interesting to conduct a more detailed financial evaluation that regards the uncertainties and financial effects of an ECTM introduction.

4.3 *Financial evaluation of ECTM*

The implementation of an ECTM program requires the acquisition of in-flight data, the development of mathematical models to normalize and compare the in-flight data to predicted values, data analysis for the detection of anomalies, alert management and computer hardware and software (Guimarães, 2015). Thus, significant investment costs and recurring costs are associated with an ECTM program. We used the precursor to failure monitoring approach of Sandborn & Wilkinson (2007) in our Monte Carlo Simulation model to determine the outcomes of implementing ECTM. Interviews were held with a technical officer maintenance of the RNLAF and a R&D researcher of the NLR who investigates the technical feasibility of the ECTM program. The case interviews show that it is difficult to estimate the numerical values of the business case, such as the quality and accuracy of the prognostic model, the development costs and the failure distribution of

Table 2. Fictive inputs for example analysis.

Time to failure	8000 hours; min 5000; max 10,000	
Operational hours	700 hours per year	
Sustainment life	15 year	
Preventive interval	6500 hours	
CBM non-recurring	€1,000,000	
CBM recurring	€100,000 per year	
Prognostic distance	20 hours (distribution width: 50 h)	
	Corrective	Preventive
Value out of service	€14,000/h	€2500/h
Overhaul costs	€2,000,000	€1,000,000
Time to repair	300 days	300 days
Time to replace	1 day	1 day

Table 3. Results of the financial evaluation.

CBM compared to	UM	PM
Return on investment	21	12
Net present value	€14M	€8M
Lifecycle cost avoidance	33%	22%
Preventive removals	N/A	– 22%
Corrective removals	– 99%	– 93%

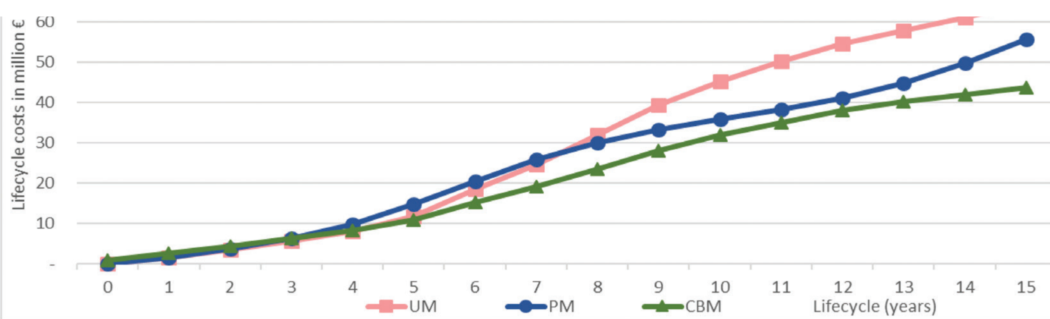

Figure 2. Comparison of lifecycle costs for three different maintenance policies. The Monte Carlo simulation shows that, over a sustainment life of 15 years, a CBM approach for the fleet of engines can be favoured over Unscheduled Maintenance (UM) and fixed-interval Preventive Maintenance (PM) (1000 simulations).

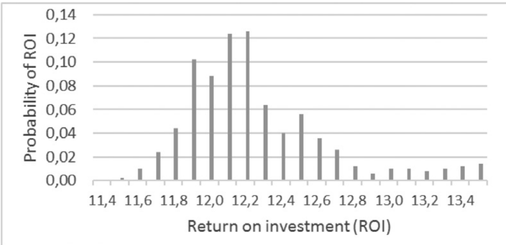

Figure 3. Sensitivity plot showing the probability of the ROI of CBM compared to a PM approach.

the asset. Because the fixed-interval policy for the engines is conservative, little data is available on the time to failure of the engines. Therefore, we used triangular distributions to estimate the component time to failures. Using triangular distributions is easier compared to more complex distributions (Marquez et al., 2007). Next to that, as the engines are halfway their lifetime, the current hours will be considered in the analysis (i.e. the hour counter does not start at 0). Because of confidentiality, we use fictive numbers (Table 2).

The results of the analysis (Table 3) show that the lifecycle costs of the CBM approach are favourable compared to the UM and PM approaches, see also Figure 2. Due to the long time to failure (~11 years), the costs of the UM approach only increase after a couple of years. Due to the high number of simulations (1000) and considering the current hours of the engines, the discrete events (i.e. failures, overhauls) are less visible in Figure 2.

A sensitivity study was conducted to determine the effects of uncertainties in the model. Figure 3 shows the probability distribution of the ROI of the CBM approach compared to the preventive maintenance policy. Also, we (quite conservatively) added twice the standard deviation (~€2M) to the CBM lifecycle costs and subtracted twice the standard deviation (~€2.5M) from the PM lifecycle costs. Third, several Monte Carlo simulations with different inputs were conducted to identify influences of errors in the input parameters on the ROI of the CBM approach.

Finally, the model was used to determine the minimum requirements for the prognostic system. These were determined by investigating what the minimum quality (expressed in the distribution width) and prognostic distance should be to obtain a positive ROI.

Together with the developers of the ECTM system, it was discussed whether it is feasible to develop a system that fulfils at least these minimum requirements. In this fictive case, a reduction of the prognostic distance by 50% and an increase in the distribution width of 50% still gives a positive ROI. Developing such a CBM system is assumed to be feasible.

5 CONCLUSION

In this paper a hybrid approach to construct a business case for CBM has been proposed based on the identified design principles in section 3.

We argue that a strategic non-financial assessment should be combined with a detailed financial modelling on a micro level. For *exploitation* of CBM techniques (applying well-known techniques), the goal orientation is to evaluate the financial contribution. Therefore, a detailed evaluation can be made, supported with traditional financial elements (i.e. ROI, NPV). For *exploration* cases (applying innovative techniques), the goal orientation is to assess the strategic (non-financial) impacts of the CBM approach on the firm. The business case can be supported with non-financial methods as a multi-criteria analysis.

The case study at the RNLAF highlights the applicability of a hybrid approach when a known technique is applied in a new context and when available data is limited. The non-financial evaluation shows that the CBM approach can increase the effectiveness of the maintenance organization while reducing costs, which is a necessity after budget cuts. It can thereby contribute to maintaining the operational availability, which has priority to the RNLAF.

The financial evaluation contributes to the non-financial evaluation by showing that although substantial capital investments are required, the CBM approach is financially favourable in the long run.

The results presented in this paper are limited as we did not include all possible effects of the CBM approach. Therefore, ongoing further research focuses on testing the proposed approach in more cases in different industrial settings.

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