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Multi-criteria weighted decision making for operational maintenance processes

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ABSTRACT

This paper proposes an approach towards multi-criteria decision making (MCDM) for operational maintenance processes. It focuses on decision alternative identification and evaluation for short time horizons, thereby addressing problems that need to be resolved in hours or a few days at maximum. This addresses a gap in literature, where MCDM methods are predominantly proposed for strategic maintenance decision making. The proposed approach addresses two distinct steps of decision making: 1) identification of decision alternatives and 2) evaluation of decision alternatives. For identification of decision options, the Boolean Decision Tree (BDT) method is selected to accommodate for the qualitative and discrete operational factors that determine the available, feasible decision alternatives in operational maintenance processes. The feasible alternatives are subsequently evaluated using the weighted sum method (WSM). The approach is applied to a Boeing 777 outboard flap damage case, using real maintenance and operational data. A decision tool has been developed and verified, showing the capability of the approach to systematically identify and evaluate operational maintenance decision making problems in a few minutes. The results suggest that the proposed approach could save in excess of 50% on decision process time, with added benefits in full identification of the available set of decision alternatives at problem onset. In addition, sensitivity analysis on the basis of a global evaluation of the weight space is provided to investigate the impact of weight settings on the decision outcomes.

1. Introduction

1.1. Context

Maintenance, repair and overhaul (MRO) organizations face difficult decisions on a daily basis, having to judge the appropriate course of action in case of events which necessitate maintenance activity, such as component failures and impact damages (Garnier et al., 2011). Maintenance decision making is complicated by scheduling constraints and resource availability, which limit the number of feasible maintenance options while adding to the complexity of identifying and selecting an optimal solution (Cassady et al., 2001). An additional problem is the fact that maintenance events are often intermittent in nature (Ghobbar and Friend, 2002): occurrences are spread far apart in time – sometimes years apart – and are related to individual components. As a result, maintenance operators lack aggregated (historical) data and experience to systematically approach maintenance event resolution: in essence, for each non-routine event, the wheel is invented again and again. This can and does lead to informal decision-making processes, with poorly defined criteria and lack of a systematic approach to choose between competing alternatives for event resolution (Stewart, 1992). As a consequence, sub-optimal decisions may result (Rastegari et al., 2013), potentially leading to significant losses in money and time. Though estimates of cost impact are sparse, several authors have highlighted the time spent searching for the right information to support maintenance decision making (Lampe et al., 2004; Taylor, 2008), indicating that 15–30% of total process time is wasted on retrieving the correct supporting information. In terms of costs, making an incorrect decision has significant implications for repair and delay costs (Cook and Tanner, 2011; Cook et al., 2009). To prevent these losses, a systematic and formalized approach for maintenance decision making has to be in place, provided that it addresses the right level of application. Theory from the field of Multi-Criteria Decision Making (MCDM) can be employed to fill this gap.

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1.2. Existing approaches to MCDM in maintenance

The current state-of-the-art in MCDM provides many methods that can serve to set up a systematic approach towards maintenance decision making. Indeed, MCDM has been employed to this purpose in the maintenance domain, but its use focuses primarily on strategic decision making and policy selection, considering the question of what is optimal in the long run, with time horizons of years rather than days (Al-Najjar and Alsyouf, 2003; Bevilacqua and Braglia, 2000; de Almeida, 2001; Pintelon and Gelders, 1992; Shyjith et al., 2008). In stark contrast, supporting decision making on the operational level in the maintenance domain – i.e., considering the question “what to do now?” with associated time horizons which are measured in days rather than years (Dekker and Scarf, 1998) – has not been covered in the state-of-the-art.

MCDM process formalizations can be boiled down to three critical characteristics as defined by Triantaphyllou (Triantaphyllou, 2000; Triantaphyllou et al., 1997).

1. Identify all possible decision alternatives
2. Establish criteria and importance in the form of weights
3. Use quantifiable evaluation of the criteria to rank each decision

With respect to the first characteristic, existing literature frequently assumes decision alternatives to be available at the beginning of the decision making process. For maintenance processes at the operational level, these alternatives are usually not known, or only partially (Stewart, 1992; Triantaphyllou, 2000; Triantaphyllou et al., 1997). Hence, a method is required to identify the full set of decision alternatives at the onset of a maintenance event.

Subsequently, the decision alternatives have to be evaluated and compared in a structured, reproducible and valid manner, leading to selection of the most appropriate option. Numerous methodologies have been proposed in literature, including numerous applications in the maintenance domain. Examples include the **Weighted Sum Method (WSM)** (Al-Najjar and Alsyouf, 2003; Ben-Arieh and Triantaphyllou, 2002; Bevilacqua and Braglia, 2000; Gorsevski et al., 2012; Govindan et al., 2015; Kabir et al., 2014; Kannan et al., 2013; Liang et al., 2015; Massei et al., 2014; Pohekar and Ramachandran, 2004; Rezaei, 2015; Tacnet and Dezert, 2011; Yager, 1988; Yager and Alajlan, 2016; Yager and Kacprzyk, 2012), **Analytical Hierarchy Process (AHP)** (Al-Najjar and Alsyouf, 2003; Bevilacqua and Braglia, 2000; Cheung et al., 2005; Govindan et al., 2015; Ho et al., 2010; Kabir et al., 2014; Kannan et al., 2013; Macharis et al., 2004; Machiwal and Singh, 2015; Majumder, 2015; Massei et al., 2014; Pires et al., 2011; Pohekar and Ramachandran, 2004; Rezaei, 2015; Saaty, 1990, 2008; Sadiq and Tesfamariam, 2009; Shyjith et al., 2008), **Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE)** (Brans, 1982; Brans and Vincke, 1985; Kabir et al., 2014; Majumder, 2015; Pohekar and Ramachandran, 2004), **Elimination and Choice Expressing Reality (ELECTRE)** (Banayoun et al., 1966; Cheng et al., 2002; Kabir et al., 2014; Majumder, 2015; Massei et al., 2014; Pohekar and Ramachandran, 2004), **Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)** (Al-Najjar and Alsyouf, 2003; Boran et al., 2009; Ching and Yoon, 1981; Govindan et al., 2015; Kabir et al., 2014; Kannan et al., 2013; Liang et al., 2015; Opricovic and Tzeng, 2004; Pohekar and Ramachandran, 2004; Shyjith et al., 2008; Yoon and Hwang, 1995), **Boolean Decision Tree (BDT)** (Aitkenhead, 2008; Barros et al., 2015; Breslow and Aha, 1997; Buhrman and De Wolf, 2002; Freund and Mason, 1999; Guisan and Zimmermann, 2000; Heiman and Wigderson, 1991; Kotsiantis, 2013; Nisan and Szegedy, 1994; Saks and Wigderson, 1986; Tsang, 1995), and **Compromise Programming (CP)** (Ho et al., 2010; Kabir et al., 2014; Majumder, 2015; Pohekar and Ramachandran, 2004). For detailed discussions of the benefits and drawbacks of each method, please refer to Triantaphyllou et al. (Triantaphyllou, 2000; Triantaphyllou et al., 1997).

A general drawback of each of these methods is that the various forms of uncertainty (Sadiq and Tesfamariam, 2009) (including ambiguity and/or vagueness) which are typically present in decision making processes are not or not fully taken into account (Celik et al., 2015; Kahraman et al., 2015; Mardani et al., 2015). To resolve this issue, fuzzy methods have been developed and combined with MCDM methods (Boran et al., 2009; Celik et al., 2015; Kahraman et al., 2015; Mardani et al., 2015). In general, fuzzy methods are used for two reasons (Mardani et al., 2015):

1. To formalize language-based weights by decision makers into a quantified approximation;
2. To aggregate multiple individual decision maker weight sets into a group decision weight set.

Both reasons are of relevance within the maintenance MCDM context. In some cases, quantified information is not available to support criteria weighting efforts. Fuzzy logic can then be used to mesh a quantitative approach with qualitative representation (Al-Najjar and Alsyouf, 2003). Moreover, in many instances it can be necessary to aggregate individual decision maker weight sets into a grouped representation, as decision making processes in maintenance are likely to be pursued in team settings, especially for capital-intensive assets. Within maintenance, application of fuzzy methods is primarily considered for inventory decision making (Kabir and Akhtar Hasin, 2013; Kannan et al., 2013) and for selection of efficient maintenance approaches (comprising strategy, policy or philosophy) (Al-Najjar and Alsyouf, 2003). However, if a single decision maker is involved and he/she can provide quantitative weights or easily explore a range of weights, the use of fuzzy logic to augment MCDM is not necessary.

1.3. Objective and structure

This paper proposes a systematic approach for maintenance decision making at the operational level, considering maintenance events which must be resolved within a time horizon of a few days. This approach is able to identify feasible maintenance options based on operational factors, and subsequently evaluates the options using weighted criteria. It consequently addresses the three gaps in research identified above: 1) maintenance decision making at an operational level, covering 2) option identification and 3) structured comparison and evaluation of decision alternatives. The contribution is application-oriented in nature, emphasizing the integration of existing methods to fill a gap in systematic decision making on an operational level within maintenance processes.

The remainder of the paper is structured in three main sections. First, the methodology section details the selected MCDM models on the basis of several application criteria and functional differences between the models. The proposed multi-criteria decision making model consists of two modules: a Boolean decision tree and a weighted sum multi-criteria decision making model. Subsequently, the Results section demonstrates how the model has been implemented, gives an application of the model on an actual damage of a Boeing 777 outboard flap as a representative example of an operational decision making process in (aircraft) maintenance, and provides sensitivity analysis. Validation with respect to the presented application is discussed in Section 4. Finally, conclusions based on the findings of the research are presented, along with recommendations for future expansion.

2. Maintenance MCDM approach at operational level

In this section the proposed approach for multi-criteria maintenance decision making at the operational level is detailed. First, the range of available maintenance options is identified using a Boolean Decision Tree (BDT) approach, as motivated in Section 2.1. This included identification of feasible repair options. Subsequently, an evaluation of alternatives is carried out using selected criteria and the Weighted Sum Method (WSM) approach.

2.1. Option identification

Option identification requires two questions to be addressed: 1) which approach is most suitable in the maintenance MCDM context? 2) Of all options identified, which options are actually feasible in practice?

2.1.1. Option identification approach

Identification of the maintenance options is based on the event attributes at the time of the repair. This includes technical attributes of the repair process at hand, as well as influencing operational factors such as logistics and asset utilization. These are typically discrete and multi-dimensional values. Some of the attributes cannot be measured using ratio scales (e.g., locations to carry out a repair), so nominal and ordinal scales must be supported. Furthermore, the selected approach should be simple and fast to use. Given the available methods covered in Section 1.2, the Boolean Decision Tree (BDT) approach is chosen to define the range of available maintenance options. It meets all requirements necessary for complete and fast option identification, having short computation time if the number of attributes is limited (Dhanisetty et al. 2016; Kotsiantis, 2013), and supporting qualitative, multi-dimensional and discrete inputs (Aitkenhead, 2008). If the number of attributes and/or large attribute ranges are considered, the amount of available options to generate and evaluate rises rapidly, with attendant consequences for required computation time.

2.1.2. Determining feasible options

Before any decision is made, the current fault or damage and operational situation has to be fully understood. Ideally a maintainer would like a wide range of repair options from which he/she can choose. However, due the severity of the fault/damage or other operational constraints, it may be determined that some repair options are infeasible (Papakostas et al., 2010). Therefore the Boolean Decision Tree is pruned to identify the repair options that are feasible.

The pruning process works as follows. In the first step of the tree all repair options are assumed to be feasible. With each consultation of the BDT attributes, the repair options list either stays the same or some of the possibilities are eliminated. This consultation process continues until the final attribute is reviewed, and the maintenance scenario for the failure event is defined with a set of possible repair options. A practical example of a pruning is given in Section 3.2.

2.2. Option evaluation

Having identified the available, feasible options, the repair options can be compared to each other based on individual decision criteria. In practice, a multi-criteria evaluation is typically more relevant. As such, this section focuses on determination of relevant evaluation criteria and an associated method, and outlines how this method can be applied relative to maintenance MCDM at an operational level.

2.2.1. Determining evaluation criteria and method

The evaluation criteria for the MCDM method to be applied should be defined beforehand. Within the maintenance domain, these criteria are highly application-dependent. Within the scope of this paper, the criteria for which the (feasible) maintenance options are being analyzed are as follows:

1. **Survivability:** probability that a part or component will continue to function over a period of time without experiencing damage.
2. **Cost:** expenses or loss in revenue directly related to the repair of an asset.
3. **Downtime:** the amount of time the asset is not producing revenue due to a repair.

This is motivated by their importance within the aircraft maintenance domain (Papakostas et al., 2010), which relates to the case study presented in this research (see Section 3). Operational maintenance processes in other industries may require different criteria for consideration.

The three mentioned criteria are quantitative, multi-dimensional, and continuous in nature. To determine the most suitable evaluation method, functional differences between methods can indicate unsuitable contenders for subsequent elimination. For instance, CP requires an ideal solution to evaluate the "closeness" of the alternatives to this ideal (Ho et al., 2010; Kabir et al., 2014; Majumder, 2015; Pohekar and Ramachandran, 2004). However, in practice there is usually never an ideal repair option – each option has benefits and drawbacks. Instead the proposed method has to compare feasible alternatives against each other. AHP, one of the most widely used MCDM methods, uses pairwise comparisons for establishing criteria weights (Kabir and Sumi, 2012, 2013; Macharis et al., 2004; Pires et al., 2011). The pairwise comparisons work well in fixing a particular weight, especially when there are is a list of sub-criteria. However, when using a limited number of decision criteria, the benefit of AHP over WSM quickly diminishes. Similarly, if one is working with a limited number of decision criteria, which can be rated in a precise, quantified way and for which the weight ranges can be explored in full, there is no impetus to work with fuzzy methods and the advantages they can bring in different contexts.

When considering the methods covered in Section 2.1, two methods are particularly suitable to identify the associated best maintenance option: the Weighted Sum Method (WSM), and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Technically speaking both of these methods can be utilized. While both would provide similar outputs in terms of option ranking, TOPSIS introduces bias towards options that are the at the extremes of ideal (acceptance) or unideal (rejection). WSM presents quantitative evaluation of the options to the decision-maker and it is up to his/her discretion to make a judgement. As it is simple to apply and allows for easy implementation and adoption by practitioners, the WSM method is selected for further use in the proposed approach towards decision making for operational maintenance processes.

2.2.2. Criteria weighting

To evaluate options with respect to each other, it is necessary to represent each option through a singular rating that encompasses the entire set of criteria. To achieve this, an aggregated weighted rating system is required. Such a system can be used to capture the importance of the contributing criteria for a decision.

In the adopted WSM approach, the criterion weights can range from 0 to 1; the sum of all the criterion weights must be equal to 1. The weights are fully customizable by the maintainer. This type of flexibility is more suited to the day to day changing circumstances under which a maintainer makes repair decisions.

Once the weights are decided upon, equation (1) shows how the final aggregate score for a maintenance option can calculated (Gorsevski et al., 2012; Yager, 1988; Yager and Kacprzyk, 2012):

$$R_{a,\text{agg}} = R_{a,\text{survivability}} \times W_{\text{survivability}} + R_{a,\text{cost}} \times W_{\text{cost}} + R_{a,\text{downtime}} \times W_{\text{downtime}} \tag{1}$$

where,

$R_{a,\text{agg}}$, aggregated rating of the repair option based on criteria weights
W, weight of decision factor, $0 \leq W \leq 1, \sum W_{\text{factor}} = 1$

This however requires determination of the individual criterion ratings R_a.

2.2.3. Criterion rating and overall evaluation

In order to arrive at the aggregated ratings of each option based on the criteria weights, first the options are evaluated separately for each individual criterion ratings R_a, followed by calculation of the aggregated score. For any given maintenance event there may be varied sets of rectification options. Therefore an normalized approach to differentiate the options from one another is required.

To achieve this, an individual criterion rating system is adopted, consisting of a scale from 0 to 1. The rating of 1 indicates the best option of the set, with 0 being the worst. If another option in the set is neither the worst nor the best, then its rating is linearly scaled based on the difference between the option with the rating of 1 and 0. To calculate the rating, two different equations can be utilized, which non-dimensionalize the criterion values (Papakostas et al., 2010). Equation (2) is used to calculate the rating of an option for a criterion that should be maximized. Conversely, equation (3) is used for a criterion that is to be minimized.

$$R_{a,factor} = \frac{x_a - X_{\min}}{X_{\max} - X_{\min}} \tag{2}$$

$$R_{a,factor} = \frac{X_{\max} - x_a}{X_{\max} - X_{\min}} \tag{3}$$

where,

$R_{a,factor}$, rating of decision factor of repair option$a$
x_a, value of the decision factor of repair option$a$
$X_{\min}$, minimum value of decision factor of all repair options
$X_{\max}$, maximum value of decision factor of all repair options

By imputation of the criteria ratings into the WSM approach (applying equation (1)), an aggregated weighted rating is arrived at. The option with the highest aggregate score is clearly identifiable to the maintainer, and can be chosen as being the best decision for a given set of weights. In this manner, the challenge of making the appropriate maintenance decision is addressed.

3. Results

In this section, the proposed approach for option identification and selection of an operational maintenance option is applied towards a practical case, which addresses an actual damage on a Boeing 777 outboard flap. In this particular case, after the damage had occurred, the maintenance company decided upon a repair option through multiple days of discussion. Concurrently, the proposed model was implemented and used to identify and evaluate the repair options, leading up to selection of the most appropriate course of action.

Section 3.1. discusses implementation of the methodology described previously, in the context of the case study. Subsequently, results are presented with respect to option identification and evaluation. A systematic sensitivity study is conducted afterwards to ascertain the influence of weight values on the overall outcome. Finally, the case study results are validated with respect to the real-life resolution of the case study problem, leading to identification of several benefits associated with the proposed approach for maintenance MCDM at operational level.

3.1. Implementation

Fig. 1 presents how the approach proposed in Section 2 has been implemented for the Boeing 777 outboard flap case study. The core steps are comprised by option identification and evaluation (steps 3–5), but these are preceded by technical analysis and followed up by actual decision making. The individual steps are described in more detail below. The approach has been implemented in Matlab, with automatic import of input information for criterion rating. Several user inputs have been implemented to help guide the decision maker in option identification and evaluation. These inputs are primarily related to identification of BDT factors and WSM weight settings. In total, the tool takes 5 s to run, provided all input information is available.

1. **Damage Found:** the first step in the maintenance process is occurrence of the initiating event: damage identification. If damage has occurred on the Boeing 777 outboard flap, this may pose a danger to the functionality of the part. Upon identification (e.g., through visual inspection), the maintenance, repair and overhaul (MRO) organization is notified to rectify the issue.
2. **Damage Evaluation:** as a second step, the MRO organization evaluates the damage. This involves dispatch of technicians with knowledge of structures to inspect the damage in detail. The technicians (with support from an engineering department) subsequently consult the Structural Repair Manual (SRM) to assess the severity of the damage and associated repair types, involving task instructions and characteristics such as the damage limits that are tolerable by the structure and the timeframe by which it has to be repaired. If necessary, the Original Aircraft Manufacturers (OAM) can be consulted if discrepancies in the SRM are discovered.
3. **Option Identification (BDT):** the Boolean decision tree approach is used to formalize the identification of all repair options. Subsequently, the tree can be pruned to remove infeasible options (see Section 3.2 for an example), yielding an overview of all feasible repair options including scheduled times of individual tasks as output. Inputs are derived from damage evaluation (i.e., technical characteristics of the event) as well as operational conditions and logistic constraints. With respect to operational conditions, internal data sources (including airline flight schedule, fleet planning, maintenance control center, and maintenance shop) are consulted to collect information related to current and future operational conditions. With respect to logistic constraints, the availability of lease, exchange or new parts is checked with external vendors, as MROs typically have limited manufacturing capability.
4. **Repair Option Criteria Rating:** the applicable decision criteria are rated for each feasible repair option. As mentioned, survivability, cost and downtime have been adopted as criteria in this case study. The rating of each criterion has been pursued in the following manner:

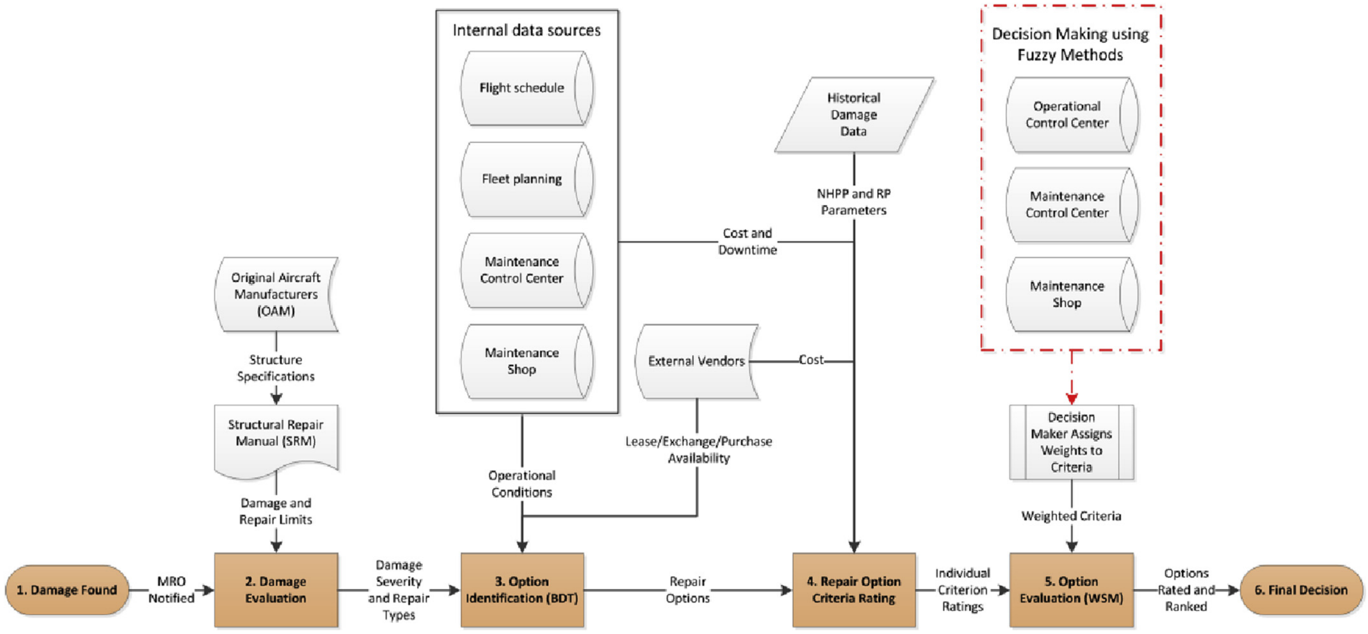

Fig. 1. Case study implementation of maintenance MCDM model at operational level.

a. **Survivability:** the majority of repair options involve temporary repair, a minimal repair action that can be modelled through a power law Non-Homogeneous Poisson Process (NHPP) to estimate survivability over time. All options have follow-up actions that restore the part to an as-good-as-new state (either through a permanent repair, or by replacement), which can modelled by a Renewal Process (RP). Historical data of part damages and repairs can be used to for trend testing, determination of the NHPP and RP parameters and goodness-of-fit testing.

b. **Cost:** within the context of the case study, cost consists of three main types: direct repair cost, aircraft grounding cost, and disruption cost. Fig. 2 gives a more detailed breakdown of these cost types. In short, repair cost is associated with the damage rectification, whereas aircraft grounding costs are associated with immediate handling of the fact that an aircraft may not be able to fly due to the incurred damage. Disruption cost is related to the network effects of the grounded aircraft: cancellation costs or swaps may be involved (Santos et al., 2017; Vos et al., 2015). To establish the ratings, data from external vendors and internal data sources of the MRO are used to provide the cost of every option, yielding precise estimates.

c. **Downtime:** downtime is associated with the total time spent out of operations. For the aircraft-centric case study, this means that repair time, installation time and waiting time during grounded operations are taken into account (see Fig. 3). The time needed for the aircraft to be grounded to perform individual tasks is established via internal data sources, again yielding precise estimates.

Then using the individual criterion rating system, all the options are normalized and compared to each other per individual criterion. This results in normalized individual criterion ratings for each feasible option.

5. **Option evaluation (WSM):** the Weighted Sum Method is applied to calculate an aggregate rating per feasible option. In practice, the weights for each criterion are determined by the decision maker in the “Decision Maker Assigns Weights to Criteria” step. An example is given in Section 3.2, with a systematic global search of all weights being explored in Section 3.3. In future implementation, this step could incorporate a multi-stakeholder perspective by using fuzzy methods to consolidate the weight inputs of different stakeholders within

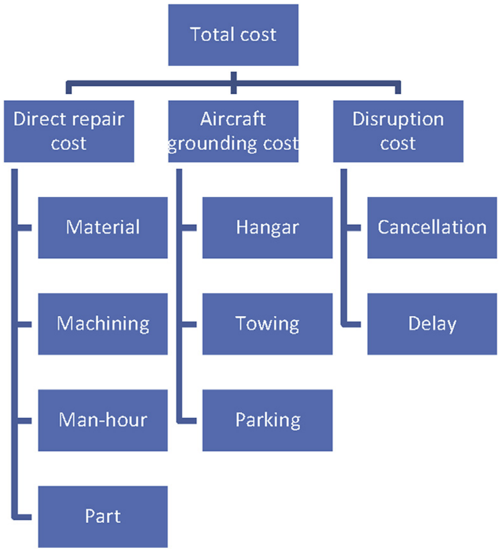

Fig. 2. Total cost breakdown.

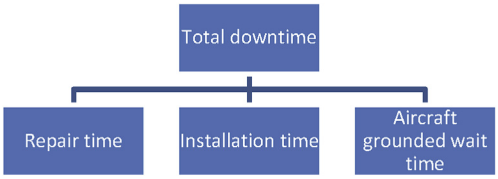

Fig. 3. Total downtime breakdown.

the MRO and the airline, but this has not been incorporated in the current case study. As an output of this step, options are rated and ranked according the aggregated ratings.

6. **Final Decision:** given a ranked list of feasible maintenance options for a specific set of weights or range of weights, the decision maker will select the preferred option.

3.2. *Case study results*

The implemented setup has been applied to a case study involving a damage on a Boeing 777 outboard flap, a composite part with high costs and complicated identification and repair considerations. Option identification is discussed first, followed by application of the WSM for option evaluation.

3.2.1. *Option identification*

The Boolean Decision Tree (BDT) is used to reveal the possible repair options based on the availability of certain facilities, actions and parts, either internally or from external vendors. For the case study there are eight attributes that are incorporated:

1. **Station of repair:** Where is the aircraft located at the moment the damage is found?
2. **Availability of permanent repair facilities:** Is the facilities for permanent repair available?
3. **Temporary repair possibility:** Is damage repairable using minimal repair techniques?
4. **Aircraft swap availability:** Is there another aircraft that can take over the planned flight of the damaged aircraft?
5. **Spare part availability:** Is there a spare part available for swapping?
6. **Lease part availability:** Is there a part available for loan?
7. **Exchange part availability:** Can the damaged part be exchanged for a discounted new part?
8. **Purchase part availability:** Is there a new part available for purchase?

Each of these factors are Boolean in nature, with only two possible answers (see Table 1).

The resulting tree is pruned using the fact that a dependency is assumed to exist between the attributes Station of repair and Aircraft swap availability. If an aircraft is at an outstation, there will not be any aircraft available for swapping flights. As such, the aircraft swap-dependent branches are pruned from the tree, reducing the total available options.

Table 1 also presents the applicable attributes for the considered case, as highlighted in **bold**. This narrows down the BDT to account for feasibility of repair options in relation to influencing operational and logistic factors. The motivation for these inputs is as follows:

- **Station of repair:** at the moment of damage, the aircraft was stationed at the home base.
- **Availability of permanent repair facilities:** the maintainer did not have access to maintenance facilities for a sufficient period of time to perform a permanent repair at the moment of damage. Note that this does not prohibit scheduling of a permanent repair at a later stage, when such facilities would become available for a sufficient length of time. This influences the overall number of feasible options, as discussed below.
- **Temporary repair possibility:** the damage was within the limits of a temporary repair as specified by the relevant documentation (SRM). This manual also stipulates that a temporary repair should be followed up by a permanent repair, leading to a sequence of repair events related to a single damage event.
- **Spare part availability:** a spare part was available in the form of a ‘cannibalized’ part from another aircraft, which was grounded for long-term maintenance at the time. Under this option, the spare flap would be inspected for condition and installed on the damaged aircraft. The damaged part would be removed for permanent repair, and installed on the grounded donor aircraft.
- **Lease part availability:** this option was available as well. Under this option, a replacement flap arrives from an external vendor a few days after it is ordered. While the lease is installed the original, damaged flap is permanently repaired. At a later stage the lease is removed to be returned to the vendor, and the original flap is re-installed.
- **Exchange part availability:** not possible in this particular case.
- **Purchase part availability:** not possible in this particular case.

Table 1
Boolean Decision Tree factors for case study, including applicable values in bold.

BDT factor	Input	
Station of repair	**Home base**	Outstation
Availability of permanent repair facilities	Yes	**No**
Temporary repair possibility	**Yes**	No
Aircraft swap availability	Yes	**No**
Spare part availability	**Yes**	No
Lease part availability	**Yes**	No
Exchange part availability	Yes	**No**
Purchase part availability	Yes	**No**

With the attributes defined and motivated, five possible operational process options for the outboard flap can be identified. These options are also dependent on consideration of two future maintenance slots for the aircraft where follow-up actions can be conducted, which occur 30 and 40 flight cycles (FC) after the damage, respectively. The resulting options for repair are shown in Table 2.

Essentially all options start with a temporary repair at the moment of damage identification (0 FC). The options differ in the type of follow-up actions and the time at which they are executed. Option 1 and 2 both have permanent repair as the follow-up action. However, option 1 executes it at 30 FC whereas option 2 executes the action at a later time, namely 40 FC. Similarly, option 3 and 4 have the same follow-up actions of installing a spare flap while concurrently performing permanent repair on the original flap at 30 FC and 40 FC respectively. Finally, option 5 involves ordering a lease flap from an external vendor, which takes time to be delivered. It has been determined that this lease flap is only available for order and installation at 30 FC. Therefore the lease flap is installed at 30FC, allowing the aircraft to remain airworthy and flying. In the meantime the damaged flap would be repaired to as-good-as-new condition. Then at 40 FC the lease is removed to be returned to the vendor and the original flap is reinstalled onto the aircraft. The five feasible repair options resulting from the BDT approach have been verified with the MRO involved in this case study, and have been confirmed to be representative of the options that were under consideration in the actual case (see Section 4 for more details).

3.2.2. *Criteria rating*

With the repair options identified, these have to be evaluated for survivability, cost, and downtime. In the context of this case study, all values required to perform criteria rating have been available as inputs – full information is available with respect to survivability data, cost and downtime.

3.2.2.1. *Survivability.* Parameter estimation for NHPP and RP has been performed on the basis of a dataset consisting of 24 Boeing 777 aircraft, spanning a period of utilization from 2006 to 2015,

Table 2
Feasible repair options for the case study settings.

		Considered time horizon (in flight cycles (FC)) for maintenance options		
		0FC	30FC	40FC
Maintenance options	Option 1	Temporary repair	Permanent repair	–
	Option 2	Temporary repair	–	Permanent repair
	Option 3	Temporary repair	Spare install with concurrent permanent repair on original	–
	Option 4	Temporary repair	–	Spare install with concurrent permanent repair on original
	Option 5	Temporary repair	Lease install with concurrent permanent repair on original	Remove lease and install original

with 96 damage occurrences for the system under consideration. The NHPP was modelled using a power law process (Rigdon and Basu, 2000), whereas the RP was modelled using an underlying Weibull distribution. Details regarding parameter estimation and goodness-of-fit testing are omitted from this analysis; the procedures followed are compliant with classical reliability theory (Rigdon and Basu, 2000).

The long term survivability is summarized in Table 3. Survivability should be maximized as the continued functioning of the considered part is critical to aircraft airworthiness – in other words, safety comes first. Because option 1 and 3 have the lowest survivability values, they are given a rating of 0. Option 5 on the other hand has the highest survivability, hence is given the rating of 1. Option 2 and 4 lie in between and using equation (2), the rating is calculated to be 0.21. Clearly, a decision based solely on survivability characteristics would prioritize option 5.

3.2.2.2. Cost. All costs have been combined together as singular value. While the actual costs of attributing elements and overall cost figures cannot be provided due to confidentiality, the total cost criterion rating of each option is stated in Table 4. Note that costs should be minimized.

Options 3 and 4, involving the swaps, have the lowest cost because grounding related costs are avoided: the aircraft can start flying as soon as the spare flap is installed. Option 5 is more than ten times as expensive as the cheapest option due to the high cost associated with a lease flap. As a result option 5 receives a rating at 0. Options 1 and 2 are more expensive than the cheapest options; using equation (3) leads to ratings of 0.89. If the decision would be based solely on cost, then option 5 is clearly the worst. Option 3 and 4 would be the best options in terms of minimizing cost, but option 1 and 2 are close contenders.

Table 3
Long-term survivability ratings for feasible maintenance options.

	Individual criterion rating
Option 1	0
Option 2	0.21
Option 3	0
Option 4	0.21
Option 5	1

Table 4
Cost criterion ratings for feasible maintenance options.

	Individual criterion rating
Option 1	0.89
Option 2	0.89
Option 3	1
Option 4	1
Option 5	0

3.2.2.3. Downtime. Similarly to cost, downtime of the aircraft related to the repair options have been combined to single values. The breakdown of individual task lengths and ground time cannot be provided due to confidentiality, but the total downtime criterion ratings are given in Table 5. Note that downtime should be minimized as well.

Options 3 and 4 have the lowest downtime and hence constitute the benchmark with rating of 1. Option 1 and 2 are significantly higher in downtime, so they are the least favorable options. Option 5, though being the most expensive option, is in the middle when considering downtime and receives a rating of 0.5.

3.2.3. *Maintenance option evaluation: example output*

Having obtained individual criterion ratings, the final element to compose aggregated scores for the feasible maintenance options is constituted by the criteria weights. In Section 3.3, a systematic sensitivity study is performed to analyze the influence of weight settings on decision model outcomes.

Here, an example case is briefly presented to provide insight into the end result the model can provide. For this case, the criteria are given the same weight, with each clocking in at values of 0.333. The resulting aggregated scores based on this set of weights are visualized in Fig. 4.

Option 4 is calculated to be the best option if a (single) decision maker values each criterion equally. Despite scoring relatively low in survivability, this option outperforms the others because of its performance in cost and downtime. In the real life case the maintainer also has chosen option 4, as detailed in Section 4. A drawback of this presented example is that the associated weights do not provide much detailed insight into the MCDM model behavior. To this end, a sensitivity analysis has been performed on the weights.

3.3. *Sensitivity analysis*

If the decision maker sets the weights directly, the best option can be computed straightforwardly, as shown in the previous section. However, a global search can generate useful insights as to the sensitivity of the WSM model output with respect to the weights. Given that the sum of all three weights of the decision criteria must equal to 1, the weight assignment space can be represented as an equilateral triangular plane in a 3D volume. Given the small number of decision criteria, a global search of entire weight assignment

Table 5
Downtime criterion ratings for feasible maintenance options.

	Individual criterion rating
Option 1	0
Option 2	0
Option 3	1
Option 4	1
Option 5	0.5

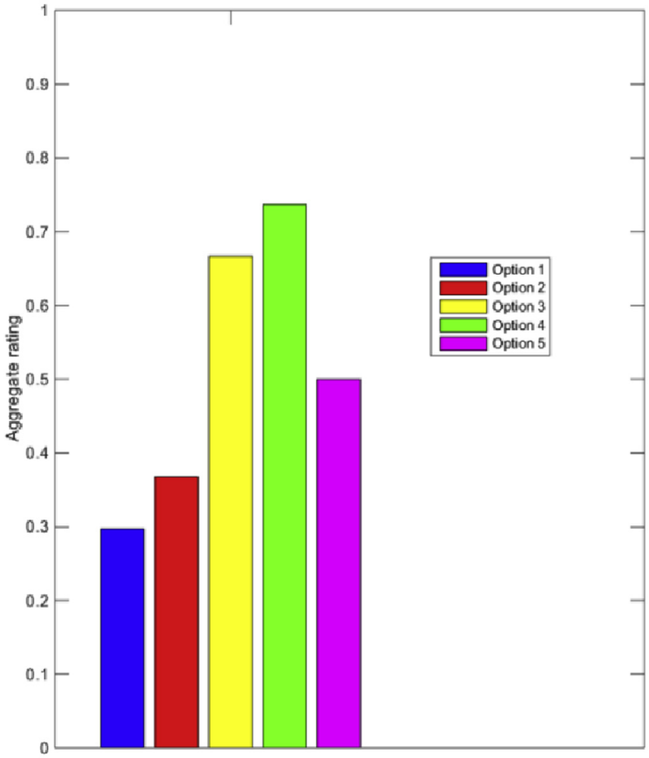

Fig. 4. Aggregate rating of all options for example case (equal priority of criteria).

space is feasible to execute, leading to full exploration of option evaluation outcomes. The results presented below have been obtained by varying the individual criterion ratings with a step size of 0.01, covering all combinations of weight settings. Computation runtime is roughly 6 s to perform the global search for the considered case.

The weight assignment space is explored in the following ways:

1. The space is explored to identify the best outcome and its respective aggregated rating for any given set of weights.
2. Similarly, the worst outcome and its respective aggregated rating for any given set of weights is analyzed.
3. Finally, the offset (or difference) between the rating of best and worst decision for a given weight case is explored, as this yields the greatest insight into the sensitivity of the outcomes with respect to weight settings.

3.3.1. *Best outcome*

When exploring the whole search space three regions can be identified, related to three best options for particular ranges of weight settings, as shown in Fig. 5.

Option 4 comes out on top for the majority of the weight cases; it only ties with option 3 when the weight of survivability is 0. Conversely, when the weight of survivability is high then option 5 is the best outcome. While it is useful to know what the best option would be for a given set of weights, the most important information Fig. 5 conveys is that option 1 and 2 are never the best option, no matter what the weights are. Interestingly, option 1 and 2 were under serious consideration by the maintainer in the real-life case. If the proposed approach would have been used to pursue decision making in the real-life case, then it would be clear from the very beginning that option 1 and 2 should not be considered.

Fig. 6 indicates the aggregate rating of the best outcome shown in Fig. 5 for any given set of weights. The rating for the best outcome decreases the further the weights move away from the corners of the solution space. The prominent green gradient aligns with the border of option 4 and 5 in Fig. 5. This shows that the best and second-best option are close to each other in that region of weights, indicating sensitivity to weight settings in that region.

3.3.2. *Worst outcome*

The global search for the worst outcome results in Fig. 7. Option 1 and 2 are indicated as the worst outcome for a large part of the search space, which is understandable in the context of Fig. 5. For the maintainer the most valuable insight from the sensitivity study is to know that option 5, which was the best option when survivability was heavily weighted, can be the worst option if cost is heavily weighted. In other words, option 5 excels in the survivability criterion but is at an extreme disadvantage when it comes to cost.

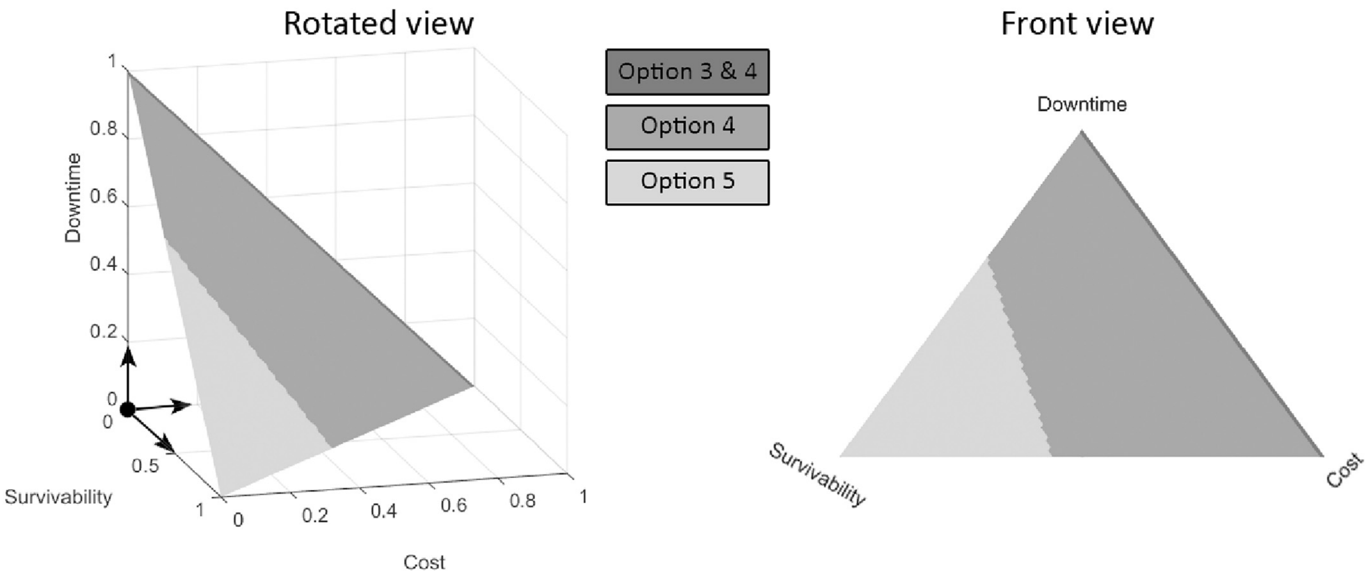

Fig. 5. Global search result for best outcome.

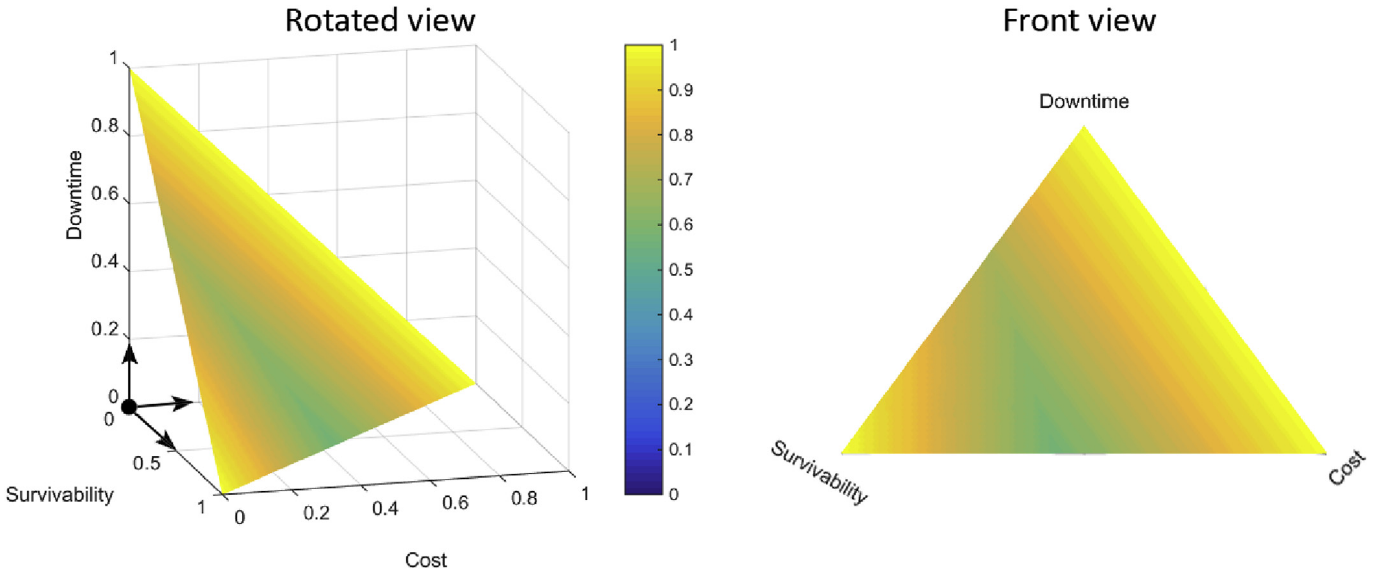

Fig. 6. Best outcome rating.

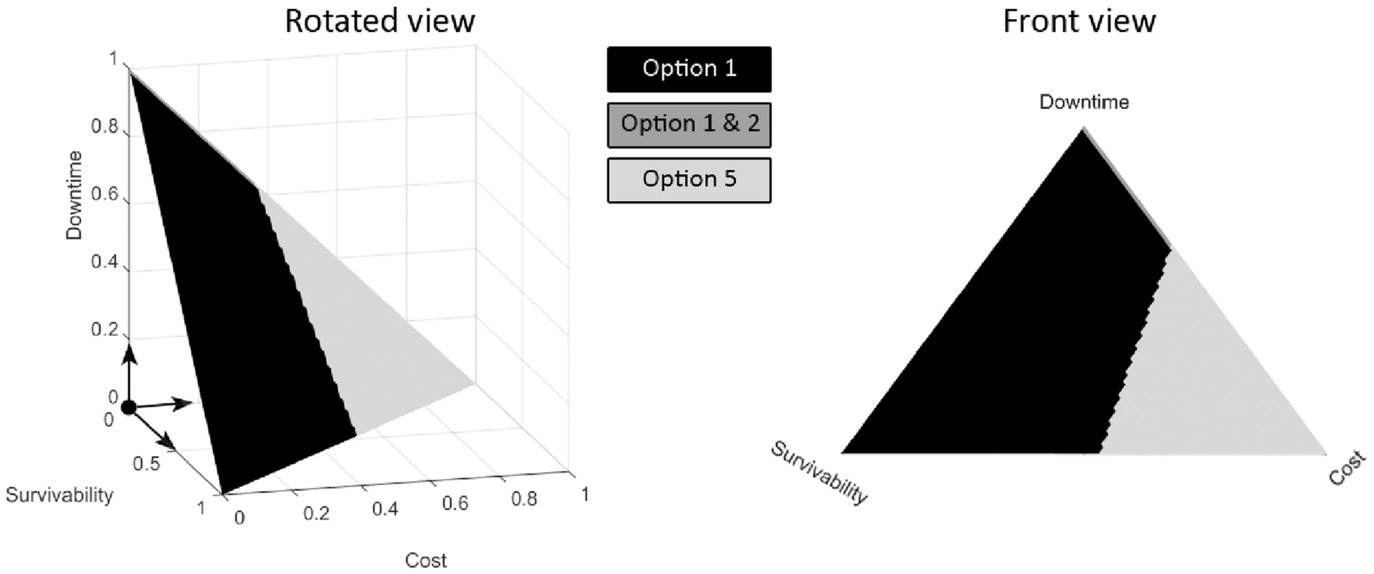

Fig. 7. Global search for worst outcome.

The aggregate rating of the worst options are given in Fig. 8. It can be seen that in the corners and across the downtime-survivability edge (where the cost criterion weight is 0), the worst outcome of Fig. 7 obtains ratings of 0. The rating of the worst option slowly increases the further away the weights move from the corners, aligning with border options 1 and 5 of Fig. 7.

3.3.3. *Offset between best and worst*

Fig. 9 shows the difference between the aggregate ratings for the best and worst outcomes for any given weight. In the corners where each of the individual criterion are heavily weighted the delta value is the highest, meaning that the best option is clearly better than the worst option. However the differences reduce further away from the corners. In fact the minimum difference between the best and the worst option rating can be as small as 0.16 close to the middle of the survivability-cost edge (where downtime criterion is weighted 0). This implies that all five options are closely rated making it harder to differentiate from each other. Therefore this informs the decision maker that he/she needs to consider downtime by increasing its weight if they want a clearly distinguished best decision.

4. Validation and discussion

The preceding sensitivity analysis presented the best outcomes for any given set of weights. It is possible to compare this information with the actual process and outcome of the damage under consideration, validating the outcome of the proposed approach as well as indicating some of its benefits.

4.1. *Validation*

In Fig. 10, a timeline is presented which gives the actual inputs, process steps and outcome of the considered case study.

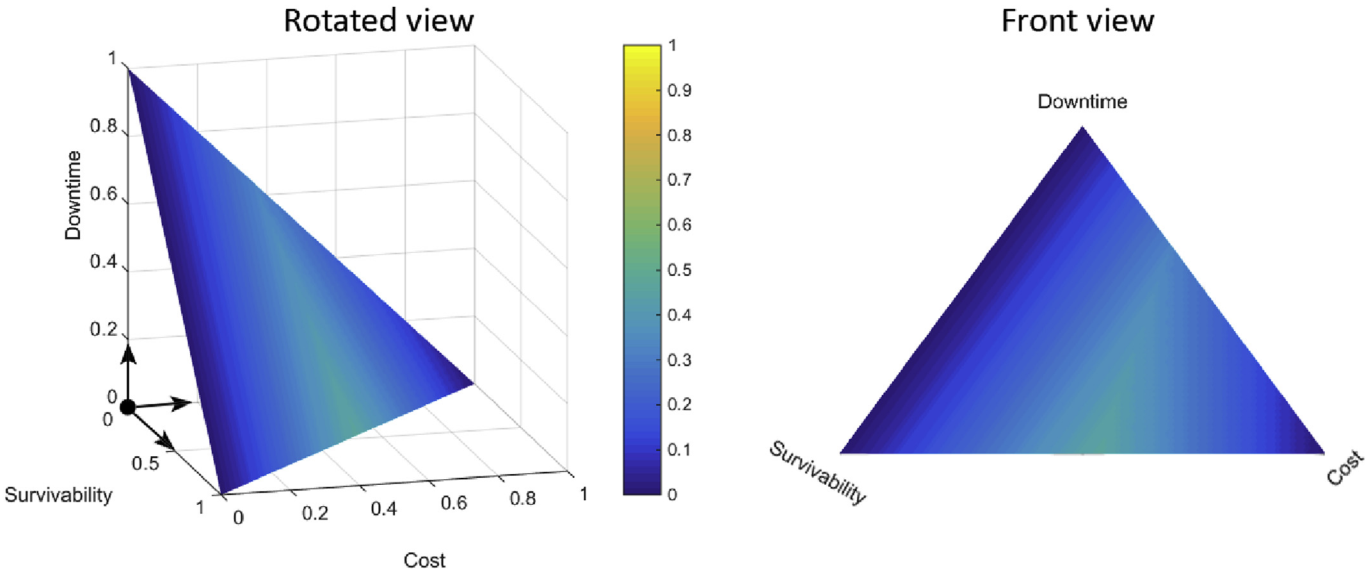

Fig. 8. Worst outcome rating.

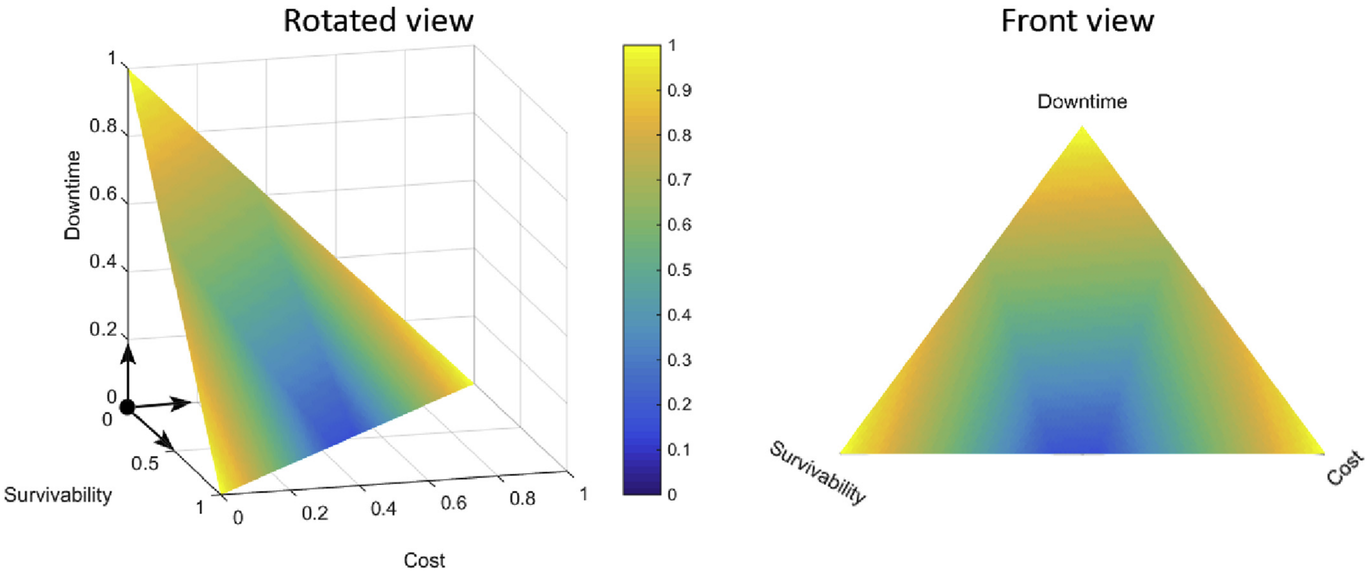

Fig. 9. Global search delta between best and worst decision rating.

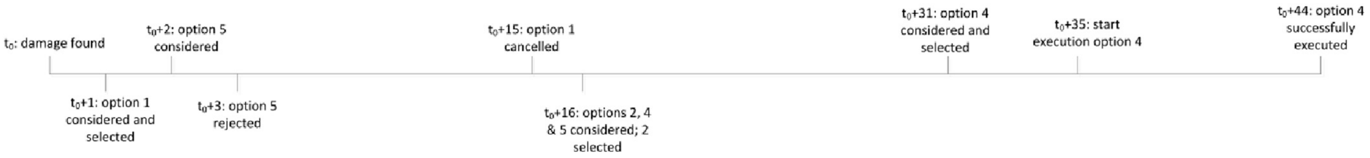

Fig. 10. Case study timeline, starting at t_0 (damage identification), with increments in stated days.

In short, the damage was found on the aircraft on a Monday (t_0) at the home station. A day later ($t_0 + 1$), option 1 (temporary repair followed by permanent repair at 30 FC) was considered and selected by the maintainer, briefly followed by consideration and rejection of option 5 (loan) two and three days later ($t_0 + 2$ and $t_0 + 3$, respectively). The loan option was rejected after receiving the cost information. The aircraft subsequently continued to fly with a temporary repair until the beginning of week 3 ($t_0 + 15$, at 30 FC) where a maintenance task was planned for the aircraft to execute the required permanent repair. However, this task was not carried out as other additional tasks took precedence. At this stage, the maintainer further explored loan and swap options (option 5 and option 4 of the BDT approach, respectively). The loan option was quickly discarded as no loan was available at that time; no swap options were identified at that time. The maintainer reverted to a permanent repair option at this point, at a later date in the timeline (similar to option 2 of the BDT). In week 5 ($t_0 + 31$ days), the maintainer saw an opportunity to exploit planned maintenance on another Boeing 777, which could act as a donor aircraft – serving as source for a swap. The original damaged Boeing 777 was brought into the hangar in week 6. The damaged flap was removed and the flap from the donor Boeing 777 was installed onto the original Boeing 777, allowing it continue operations. Later in the week the permanent repair on the original damaged flap was undertaken, with the donor Boeing 777 receiving the repaired flap in week 7.

When comparing the actual process to the proposed approach elucidated in Sections 2 and 3, several aspects are noteworthy. It should be noted here that the maintenance company involved in this study has recognized all subsequent points.

- The requisite information for the proposed approach (BDT factors, criteria rating inputs, and weight factors) were all available at or near the onset of the decision problem. In this particular case, the proposed approach could have identified all options on the first day, with evaluation being feasible when cost information arrived from external parties (end of week 1). This compares favourably to the actual process, in which 5 weeks were spent in iterating the decision making process. In other words, the proposed model would have indicated that option 4 was the best outcome after a few days (upon receipt of vendor cost information). In contrast, it took 5 weeks for the maintainer to consider that option seriously and select it for the considered case.
- Multiple options were considered at different points in time in the actual situation, even though all information for option identification was available at the onset. For instance, it was known from the very beginning that another Boeing 777 was planned for maintenance in week 5. This would have provided a spare swap possibility, but this option was only identified much later. The lack of a systematic approach allowed for serious consideration of suboptimal choices, and more favorable options to be completely missed out. This is primarily observed in the initial decision to pursue option 1, which was shown to be unfavourable in Sections 3.2 and 3.3, and the consideration of option 2 in week 3, which is similarly unfavourable. The model on the other hand would identify all the options on day 1, with evaluation being possible several days later. Under various weighted priorities, either option 4, option 5 or option 3 would be preferred (as shown in Section 3.3.).

4.2. Discussion

A number of critical findings can be established from the comparison between the actual case and the proposed approach.

- *The maintainer did not have a structured approach towards option identification.* Even though all information was available at the onset, much information was not taken into account initially (e.g., the possibility of executing a swap by correlating the issue with maintenance planning of other 777's; the possibility of executing a permanent repair at different points in time (30 FC and 40 FC).
- *The maintainer did not have the capability to systematically evaluate the decision alternatives.* Insufficient information was gathered to support the decision making process, even though all requisite cost, downtime and survivability information was available at or shortly after the onset of the decision process. In being unsuccessful in option identification, the maintainer zoomed in on options 1 and 2 prematurely, with option 5 being investigated briefly before being discarded on the basis of cost (without a formal evaluation with respect to the other options).
- *The maintainer spent too much time in the decision process.* The full process itself took 7 weeks to complete, but several factors contributed to this beyond the decision process itself. More importantly, therefore, is the fact that multiple iterations were undertaken for the decision process, involving substantial man-hour effort from several individuals. If the approach proposed in this paper would be followed, the decision making process could be completed in a few man-hours, with about 30 s of computation time necessary when all inputs are available. The actual process consumed many more man-hours, though exact estimates cannot be given as the maintainer did not track time for all involved processes. However, it is safe to say that a conservative estimate would see in excess of 50% savings on time spent in the decision making process. This estimate allows for the time spent gathering the necessary information for option generation, criteria rating and option evaluation.

Though individual circumstances may differ, these findings are typical of maintenance MCDM at the operational level. As such, a systematic approach such as the one proposed in this paper may offer significant benefits to maintainers and associated stakeholders in resolving maintenance decision making problems at the operational level.

5. Conclusions

Maintenance companies face the continued challenge of readily identifying all feasible maintenance options for maintenance processes at the operational level, where short time horizons (spanning several days maximum) are involved. Furthermore, maintainers typically lack a systematic approach towards being able to make a final decision from the available set of decision alternatives. Hence, an approach has been developed that is able to 1) identify the maintenance options feasible under operational constraints and 2) evaluate the options systematically to suggest maintenance decisions. The novelty of the proposed model lies in the ability to identify, evaluate and select through the use and integration of two different MCDM methodologies: a Boolean Decision Tree (BDT) for option identification and the weighted sum method (WSM) for selection of final option. Additionally, the model is catered towards application on maintenance processes at an operational level, rather than focusing on a strategic maintenance level. This addresses a specific gap in existing literature.

A self-contained tool has been developed that can identify feasible alternatives and evaluate these options using the WSM approach to suggest a maintenance decision. To test the approach in an operational setting, a case study on a Boeing 777 outboard flap has been executed. The validation case shows that several benefits of the proposed systematic approach towards maintenance decision making at the operational level. The primary benefits are accurate option identification at problem onset, a full evaluation of all options, and significant time savings in decision making compared to more unstructured, iterative approaches.

There are three major recommendations for future research regarding this model: implementing pair-wise comparison for determining standard weights, allowing for fuzzy inputs and adopting a probabilistic Boolean decision tree. Currently the weights have purposefully been designed to be set manually by the maintainer or searched globally. However, with sufficient data from multiple stakeholders a pairwise comparison approach could unveil commonly recurring sets of criteria weights for any given part. Moreover, the current model assumes that all the exact inputs values for survivability, cost, and downtime are known, which is true for the specific application presented in this paper. However, to make the model more adaptable and generalizable, fuzzy inputs can be utilized to accommodate for estimates from multiple sources. Also the weights for the criteria can be treated as fuzzy input, especially when taking linguistic formulation of priorities from multiple decision makers. For now the model is limited to a singular group-weighted criteria, but to adjust for this limitation a global search has been implemented. As for the Boolean decision tree, it is designed to be deterministic, so it has to be run with every damage enquiry. However, if the probabilities of each scenario identification factors and their links are known, a long term strategic plan which incorporates frequently recurring scenarios can be created.

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