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Multi-criteria weighted order based maintenance decision making

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Abstract

Decision making in daily maintenance requires consideration of multiple factors. The importance of each of the factors fluctuates depending on the repair scenario and the needs of the maintainer. In order to include the prioritisation of multiple criteria, a weighted decision making model is developed. The model evaluates all repair options and rates them individually for three decision making factors: survivability, cost, and downtime. The factor ratings are aggregated using designated weights, resulting in a final score for each of the repair options. This type of decision making evaluation provides flexibility in considering repair options that may otherwise be deemed unfavourable because of one factor. Case study results show one of five considered options as the best, for three of the four weight sets. The resulting best option of the other weight set demonstrates that definition of best repair is dependent on the priority of decision factors.

Keywords: decision making, decision factors, weighted order, multi-criteria, structures repairs, survivability, repair cost, repair downtime, aggregated

Introduction

When making a repair decision on a component or structure, a maintainer faces multiple factors that influence the final decision. On top of that, identification of the best repair decision can easily become a subjective matter, open to interpretation from different perspectives [1]. The reality is that no one factor is always the determining factor when it comes to maintenance decision making of all scenarios. Hence the maintenance decision making has to be fluid and flexible to enable dynamic prioritisation in decision making.

This paper explores prioritisation of decision making factors for structural repairs. Therefore the main question being researched is as follows: How can maintenance repair options be identified in light of varying levels of priority with respect to decision making factors? In order to define the prioritisation of the decision factors, weighted operators are implemented. This approach has been utilised in other domains such as multi-objective programming for supply chain optimisation [2] and landfill site selection for waste management [3]. In this case the multi-criteria decision making is being implemented for aircraft maintenance repair decisions. Hence the main objective is to develop and test a decision making model that accounts for all maintenance decision factors using flexible weighted operators.

First the methodology of the weighted decision making model is described. The different multi-criteria model factors are discussed followed by the weighted order approach to evaluating the factors for final decision making. The model is subsequently applied in a case study addressing the Boeing 777 composite outboard flap. The results of the test case are discussed showing the applicability of the model. Finally the conclusions and recommendations for future research are presented.

Methodology

Multi-criteria model factors

A multi-criteria decision making process can incorporate a vast number of factors. In general, the more numerous the factors, the more accurate the model becomes. However, including a large number of factors can quickly make the model complex and dependent upon information that is not always available. Hence, in the interest of reduced complexity, the three most mutually exclusive maintenance decision factors chosen for the decision making model proposed in this paper are: survivability, cost, and downtime (see Fig. 1). Survivability is a reliability based probability that a structure will survive over a certain period of time. Cost encompasses direct repair costs and any flight network effecting cost such as flight cancellation or delay. Finally downtime is the amount of the time the aircraft is grounded for the repairs.

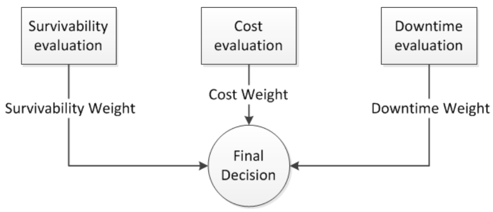

Fig. 1: Multi-criteria model factors as inputs for the final decision

Survivability

Survivability is the measurement or probability that a component will continue to function without the need for a repair action. The repair actions themselves have an associated repair effectivity that directly affects the survivability. The repair effectivity can be generalised into two major categories: as-good-as-new and as-bad-as-old. As-good-as-new would be considered restoring a part to its original performance or state. As-bad-as-old is application of minimal repair, just ensuring the functionality of the component but the performance is just as it was before failure. The methodology employed for the two repair philosophies are shown in Table 1[4, 5].

Table 1: Repair philosophies and respective survivability calculation methodologies

Repair philosophy	Methodology	Characterising equations [4, 5]
As-good-as-new	Renewal process	$\lim_{t\to\infty} P\left(N(t) < a(t)\right) = \Phi(y)$ (1) $a(t) = \frac{t}{\eta} + y\sigma\sqrt{\frac{t}{\eta^3}}$ (2)
As-bad-as-old	Non-homogenous Poisson Process	$\lambda(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1}$ (3) $P(N) = \frac{e^{t\lambda(t)}\left(t\lambda(t)\right)^N}{N!}$ (4)

Cost

Attempts were made to tie overall cost to the damage size. However, due to the lack of consistent data and the large variance within useable data, the tool prioritises the use of manual cost inputs for decision making evaluation. A simple cost breakdown is shown in Fig. 2. All costs are directly related to the aircraft in question and so any affect to other aircraft or component due to repair are not taken into account.

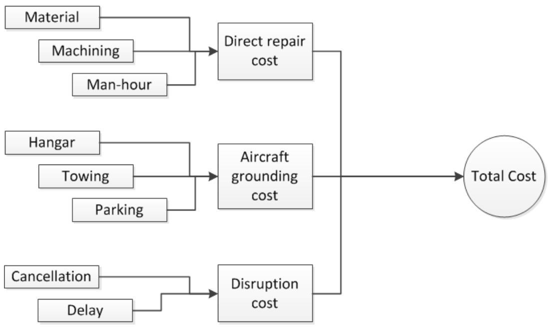

Fig. 2: Cost breakdown

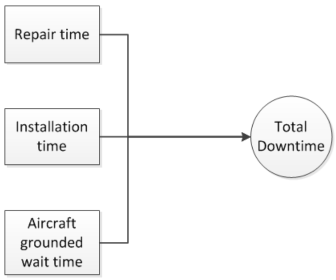

Fig. 3: Total downtime inputs

Downtime

Similar to cost, downtime is kept as a manual input for the maintainer in the tool. Once again downtime is dependent upon many factors that typically exhibit a large variance. Hence to simplify the tool the maintainer inputs estimates of minimum time the aircraft is expected to be grounded. This is can be calculated using the amount of shifts (8 hours per shift) it takes for the repair to be applied, to exchange the faulty structure, and amount of time the aircraft is grounded waiting for the repair to begin (for example, arrival of spare parts).

Weighted order

Before the weighted order is applied to each of the three factors, a measurement scale for the comparison of different repair options has to be established. The measurement scales from 0 to 1, where 1 represents best option for that factor and 0 means the worst. Options that are neither the worst nor the best lie somewhere between the scale. Equation (5) provides the rating for when a factor is preferred to be maximised and equation (6) is for rating factor that is to be minimised.

$$R_{a,\,factor} = \frac{x_a - X_{\min}}{X_{\max} - X_{\min}} \tag{5}$$

$$R_{a,\,factor} = \frac{X_{\max} - x_a}{X_{\max} - X_{\min}} \tag{6}$$

Where,
$R_{a,\,factor}$, decision factor rating for evaluated repair option, *a*; x_a, factor value of the evaluated repair option, *a*; $X_{\min}$, minimum factor value of all repair options; $X_{\max}$, maximum factor value of all repair options.

Take for example three options for repair tasks are being evaluated for cost, option 1 costs 100$, option 2 is 40$, and option is 60$. Costs should be minimised, so equation (6) is used.

Then since option 2 is the cheapest ($X_{\min}$) it is chosen as the benchmark and receives a rating of $R_{2,\text{cost}} = 1$, the most expensive is option 1 ($X_{\max}$) and receives a rating of $R_{1,\text{cost}} = 0$. Using the benchmarking rating equation (6) the option 3 would receive a rating of $R_{3,\text{cost}} = 0.67$.

This rating evaluation procedure of all three factors are carried out for all available repair options. Each repair option would then receive a score for survivability, cost, and downtime, which are then aggregated into a final weighted score using equation (7) [3, 6, 7].

$$R_{a,\text{agg}} = R_{a,\text{survivability}} \times W_{\text{survivability}} + R_{a,\text{cost}} \times W_{\text{cost}} + R_{a,\text{downtime}} \times W_{\text{downtime}} \quad (7)$$

Where,
$R_{a,\text{agg}}$, aggregated rating of the repair based on all factors; W, weight of a decision factor and must comply with: $0 \le W \le 1, \sum W_{factor} = 1$

The weights are under the discretion of the maintainer. Equal priority would mean that all factors are weighted equally. However, if the maintainer is more concerned about a specific factor, then this factor can be weighted heavily. This gives the maintainer full flexibility in examining which repair option is best under different priorities.

Test case description

A case study on a Boeing 777 outboard flap was carried to test the applicability and functionality of the proposed weighted decision making. The flap had incurred a damage that was within temporary repair limits. At the moment of the damage five repair options are considered. Option 1 and 2 involved a temporary repair followed by permanent repair. Option 3 and 4 would have a spare flap be swapped after temporary repair. While the aircraft is flying with the spare flap the damaged flap would be restored with a permanent repair in shop. Lastly, for option 5 after temporary repair the damaged flap is removed and a loan flap is installed to make the aircraft airworthy again. The damaged flap is sent to the shop for permanent repair and later is reinstalled on the original aircraft, removing the loan flap. A summary of the five options is given in Table 2.

Table 2: Action summary at different times (flight cycles, FC) for each repair option

	Initial Damage (0FC)	*Maintenance Slot 1 (30FC)*	*Maintenance Slot 2 (40FC)*
Option 1	Temporary repair	Permanent repair	-
Option 2	Temporary repair	-	Permanent repair
Option 3	Temporary repair	Spare flap swap	-
Option 4	Temporary repair	-	Spare flap swap
Option 5	Temporary repair	Loan flap install	Restored original flap install

All five options carry out temporary repair at the moment of the damage. The aircraft is still airworthy for another 400 flight cycles (FC) with this repair. However, the temporary repair must eventually be followed by a permanent repair. The maintainers have identified two different maintenance slots for follow-up actions: maintenance slot 1 (MS1) at 30FC and the other (MS2) at 40FC. This relates to the observed sequences of repair operations in Table 2, generating five distinct options for this particular case. Note that option 5 is the only repair option with two follow-up actions.

Results

The following are results output by the model for the test case of the Boeing 777 outboard flap damage. Table 3 provides a summary of all the decision factors values for each of the repair options in the long term. These values are used to calculate the aggregate ratings under different priorities shown in Fig. 4: equally weighted, survivability weighted, cost weighted, and downtime weighted. For equally weighted decision making all factors have a $W_{factor} = 0.33$. As for single heavy factor decision making the W breakdowns to 0.8, 0.1 and 0.1, where the $W_{factor} = 0.8$ is for the prioritised factor.

Table 3: Long term decision factor values for each of the repair options

	Option 1	*Option 2*	*Option 3*	*Option 4*	*Option 5*
Survivability	0.3145	0.3150	0.3145	0.3150	0.3172
Cost ($)	30061	30061	14490	14490	158798
Downtime (hours)	49 hours	49 hours	17 hours	17 hours	33 hours

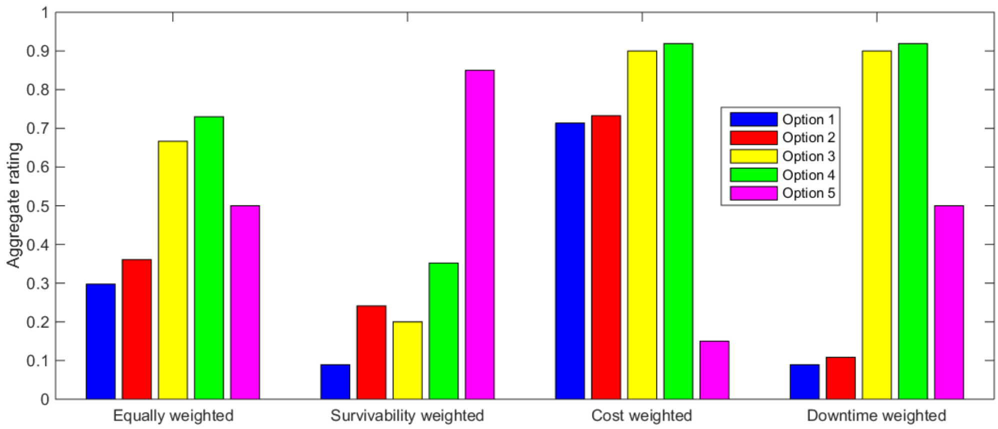

Fig. 4: Aggregate rating of repair option for multiple prioritisation

- **Equally weighted:** For equal priority factors, option 4 is most highly rated option with a score of 0.73. Option 3 and 4 are both the cheapest and least time consuming repair option hence they ranked highest in the set of options. Option 4 edged out over Option 3 because it granted slightly higher long-term survivability.
- **Survivability weighted:** When prioritising survivability, option 5 is a clear winner in the weighted rating system with 0.85. Survivability has been weight 80%, cost and downtime are weighted 10% each. Hence despite being more than 5 times more expensive than the next cheapest option, due to the higher achieved survivability and second lowest downtime option 5 is easily wins a survivability weighted decision making.
- **Cost weighted:** A cost weighted decision making ranks option 4 as the best option with 0.919. Though having the same costs as option 3, option 4 has slightly higher survivability. The cost weight significantly affected the favourability of option 5. Due to drastically high cost it only receives a rating of 0.15.
- **Downtime weighted:** Once again for the downtime weighted decision making option 4 is the most preferred with 0.919, closely followed by option 3 at 0.9. Essentially, option 3 and 4 equally rated for cost and downtime weighted decision making because the only difference between the two options is the survivability. Note that option 1 and 2 never win any of the categories: they force an aircraft to be on ground for the longest

time without excelling in the other categories. Hence, they are never an ideal solution to any of the expressed perspectives.

Conclusions & Recommendations

In aircraft maintenance the decision making is dependent on multiple factors. Each of these factors are prioritised under the discretion of the maintainer based on the needs of the time. Therefore a quantifiable approach to evaluating all repair options is needed such that all the priorities are satisfied. Consequently a weighted maintenance decision making has been developed and tested on a Boeing 777 outboard flap, taking into consideration three decision factors: survivability, cost, and downtime.

The test case involved five different repair options that are evaluated and given an aggregated rating based weights of the decision factors. Four weight cases for decision making are applied: equally weighted, survivability weighted, cost weighted, and downtime weighted. One of the five repair options satisfied equally weighted, cost weighted, and downtime weighted consistently because high favourability rating in cost and downtime factors. However, when considering survivability weighted decision making the repair option with the highest cost and second highest downtime was chosen to be the optimum decision. This exemplifies that based on the weights of the factors, a seemingly unfavourable option can be identified as the best for a given set of priorities.

The model can be expanded using formal approaches to criteria weighting in multi-decision problem, such as the analytical hierarchy process. Such methods would allow the maintainer to identify the standard optimum weights for each of the factors, but might entail a loss of flexibility. However, the standard weights can be customised for differing perspectives such as safety oriented or downtime oriented decision making, enabling standard weight sets relating specifically to the operations of an airline.

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