Impact damage repair decision-making for composite structures

Predicting impact damage on composite aircraft using aluminium data

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PREDICTING IMPACT DAMAGE ON COMPOSITE AIRCRAFT USING ALUMINIUM DATA

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PREDICTING IMPACT DAMAGE ON COMPOSITE AIRCRAFT USING ALUMINIUM DATA

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology,
by the authority of the Rector Magnificus, prof. dr. ir. T. H. J. J. van der Hagen,
chair of the Board for Doctorates,
to be defended publicly on
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By

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Knowing how to think empowers you
far beyond those who know only what to think.

Neil deGrasse Tyson

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SUMMARY

There is a growth in the use of composites for the new generation of wide-body aircraft such as the Boeing 787 and Airbus A350. This shift from using aluminium as the primary material is motivated by the benefits of using composites in design, manufacturing and operations. Composites offer the aircraft manufacturer the ability to create more complex shapes and optimise the design such that it is light-weight. This, in tandem with other design improvements, leads to lower fuel burn. Consequently, airlines see the advantage of these new aircraft to reduce their operational cost. Therefore, as airlines continue to renew their ageing fleets of aluminium aircraft, there is going to be an increased need for composite maintenance. However, fulfilling the increased demand for composite repairs is impeded by limited availability of historical damage data, due to the young operational age of these aircraft. Composites are particularly sensitive to impact damage, and understanding the likelihood and the consequence of this type of damage is valuable for maintenance processes such as repair decision-making. The purpose of this dissertation is to predict the risk of impact damage for future composite aircraft and use it to substantiate maintenance decision-making in an operational setting.

Methodologically, this dissertation takes a novel approach to addressing the limited composite damage data by considering a conversion process for historical data regarding aluminium damage. Aluminium aircraft have been flying for more than 20 years, in which time Maintenance Repair and Overhaul (MRO) organisations have gathered historical damage data. Using the known aluminium structural properties and damage dimensions, the impact event can be reverse-engineered to deduce impactor characteristics (size and energy). With the assumption that both generations of aircraft will operate under similar conditions, composite aircraft are expected to be damaged by similar impactors. Thereby, predicted impactors can be used to induce impact events on a composite structure and predict the corresponding damage and repair consequence. Applying the conversion process across the entire aluminium damage dataset results in a composite pseudo-damage dataset, which enables the prediction of impact risk for composites.

The obtained composite pseudo-damage dataset can provide the necessary likelihood of damage instance to substantiate maintenance processes such as repair decision-making. The selection of a repair option is influenced by damage severity, but also the operational constraints at the time of decision-making. These constraints dictate the set of feasible options that go on to be evaluated against specific decision criteria. In this research, these criteria are set as cost, survivability and downtime. This research proposes a novel decision process formulation which combines Boolean Decision Tree and the Weighted Sum Method to respectively identify and evaluate repair options. The decision-making model introduces a global weight search algorithm that evaluates the repair options for all weighted combinations of the decision criteria, providing the decision-maker with a complete overview of all options.

These proposed methods have been tested, verified, and validated through case studies to analyse their performance. The conversion process from aluminium to composite damage was successful for over 90% of the sample damage data. The comparison of impact risk between aluminium and composite revealed drastic differences, where 25% of the impactors led to no visible damage on the composite. This indicates either superior resistance to damage for composites, or possible internal damage that may require additional non-destructive inspection (NDI). Subsequently, the decision-making model was tested for a damage case on an outboard flap. The model identified five feasible options and when evaluated, two options dominated the best option output of the global weight search algorithm based on the decision criteria. The run-times for both steps of the decision-making process was considerably shorter compared to the several days it took for the real-life process. Furthermore, the model indicated the two worst options of that scenario, but without the model the same options were seriously considered by the decision-maker, exposing the fact that the lack of quantitative analysis can lead to suboptimal decisions. In the end, these methods were directly applied to the development of a decision-making tool called Airmedt (**Air**craft **M**aintenance **E**valuation and **D**ecision **T**ool). The purpose of the tool is to demonstrate the potential application of the research in practice. Currently it is a standalone tool capable of conducting evaluations on repair options with known scenario conditions. With future implementation with information systems the decision-making process can be partially automated and integrated to involve all stakeholders such as the maintenance shop, Operational Control Centre (OCC), Maintenance Control Centre (MCC), and external vendors.

The research shows promise in the idea of using aluminium data to help future composite maintenance, but there are lessons learnt that must be addressed in moving forward. The biggest hurdle in this research was not the lack of aluminium data, but it was the low descriptive quality of the data. A large portion of the data (nearly 75%) was unusable because the damage descriptions with the dimensions were either incomplete or missing altogether. This highlights the need for more detailed data collection as it can enable better analysis and provide insights for improvements in the future. Another aspect to be addressed is the assumptions that are made to obtain the risk of impact on composite aircraft. The damage modelling assumes a spherical impactor and flat plate to simplify the analysis, but the curvature of aircraft structures and different material shapes may influence the damage results. Furthermore, the consequence is fixed in terms of direct repair cost but a dynamic approach to risk modelling can lead to a broader perspective on impact risk. The dynamic nature can also be extended to the option identification process, adapting it to identify or predict possible best- and worst-case scenarios, so that the decision-maker can react quickly to changes.

Despite these limitations, the methods discussed in this dissertation explore a unique opportunity to advance the field of composite maintenance. Using aluminium damage data to predict composite damage augments the knowledge for future maintenance on composite aircraft, both in terms of the frequency and the types of repairs that will be required in an aircraft's lifetime. The obtained damage risks can be further extended to other applications such as setting design and repair limits for aircraft's structures, prioritising area and frequency of inspection on the aircraft, or even identifying specific risk sources around an aircraft and setting mitigation plans to improve the operational envi-

ronment. The specific application explored in this thesis is repair decision-making. The proposed method enables the decision-maker to have a broader overview of daily decisions. These decisions are enhanced by thoroughly identifying all repair options and analysing them against quantifiable decision factors. Thereby substantially decreasing the time spent on decision-making while increasing the rationale and understanding behind selecting a particular option. These advantages are explored and supported by the case studies conducted during the research. The current challenge of large scale composite maintenance is directly addressed by exploiting the better availability of aluminium maintenance data through the deductive-inductive process, informing future maintenance practices such as repair decision-making.

SAMENVATTING

De nieuwe generatie wide-body vliegtuigen maakt in toenemende mate gebruik van composieten als constructiemateriaal, zoals in de Boeing 787 en Airbus A350. De verschuiving van aluminium naar composieten als primair materiaal wordt gemotiveerd door de voordelen welke het gebruik van composieten met zich meebrengt voor ontwerp, productie en operaties. Composieten maken het voor de vliegtuigproducent mogelijk om complexere vormen te creëren en het ontwerp zo licht mogelijk te maken. Dit leidt, in combinatie met andere ontwikkelingen in vliegtuigontwerp, tot een lager brandstofverbruik. Omdat brandstofverbruik voor vliegmaatschappijen een significante kostenpost is, wordt het vernieuwen van de verouderde vloot versneld om de operationele kosten te verlagen. Deze ontwikkeling leidt naar een hogere vraag naar het onderhoud van composieten. Het vervullen van deze vraag wordt echter bemoeilijkt door beperkte beschikbaarheid van historische data omtrent schades aan composieten, doordat deze relatief kort in gebruik zijn. Composieten zijn in het bijzonder gevoelig voor impactschade wat begrip van de kans op, en consequenties van, dit soort schade van groot belang maakt voor onderhoudsprocessen zoals reparaties en de daarbij behorende besluitvorming. Het doel van deze dissertatie is om het risico op impactschade voor toekomstige composieten vliegtuigen te kunnen voorspellen, en om dit te gebruiken om een overwogen beslissingsproces betreffende onderhoud in een operationele context te kunnen ondersteunen.

Vanuit een methodologisch perspectief wordt in deze dissertatie een nieuwe benadering voorgesteld om het probleem van beperkte data te ondervangen. Deze benadering bestaat uit een conversie van historische data betreffende schade op aluminium structuren. Oudere aluminium vliegtuigen, zoals de Boeing 777 zijn al meer dan 20 jaar in bedrijf. In dit tijdsbestek hebben zogenaamde Maintenance, Repair and Overhaul (MRO) organisaties historische data over impactschade verzameld. De daaruit vloeiende informatie over schadedimensies kan in combinatie met bekende materiaaleigenschappen van aluminium worden gebruikt om eigenschappen (grootte; energie) van de impactor te schatten. Aannemende dat beide generaties vliegtuigen op een soortgelijke manier zullen worden ingezet, is het te verwachten dat soortgelijke impactors schade zullen veroorzaken bij vliegtuigen van composietmateriaal. Als gevolg van deze veronderstelling is het mogelijk om de voorspelde impactors te gebruiken om impactgebeurtenissen op een composietstructuur te voorspellen, en de hierbij horende schade- en reparatiebenodigdheden in te schatten. Het toepassen van dit conversie-proces op de volledige dataset met impactgebeurtenissen op aluminium structuren levert een zogenaamde pseudo-damage dataset op, welke kan worden toegepast om het risicoprofiel van impactschade op composietstructuren te voorspellen.

De zodanig verkregen pseudo-damage dataset kan worden gebruikt om noodzakelijke informatie over de kans op impactschade te generen en vervolgens te gebruiken om onderhoudsprocessen zoals besluitvorming over reparaties te ondersteunen. Het

selecteren van een reparatie-optie wordt beïnvloed door de ernst van de schade, maar ook door operationele beperkingen die gelden tijdens het maken van een besluit. Deze beperkingen dicteren welke opties haalbaar zijn. Deze opties kunnen vervolgens worden geëvalueerd ten opzichte van specifieke besluitvormingscriteria. In dit onderzoek worden de kosten en de geschatte levensduur van de reparatie, alsmede de downtime ten gevolge van de reparatie meegenomen als criteria. Dit wordt meegenomen in een innovatieve formulering van een besluitvormingsproces voor het identificeren en evalueren van reparatie opties. Hierin wordt gebruik gemaakt van een combinatie van zogenaamde Boolean Decision Trees and een Weighted Sum Method. Het besluitvormingsmodel introduceert een globaal zoekalgoritme om alle gewogen combinaties van de besluitvormingscriteria te evalueren. Hieruit verkrijgt de besluitvormer een compleet overzicht van alle opties.

De besproken methodes zijn getest, geverifieerd en gevalideerd in scenarios waarbij de prestaties zijn geanalyseerd. Het omzettingsproces voor aluminium naar composiet impactschade is succesvol voor meer dan 90% van de geteste dataset met impactschades. De vergelijking qua impactrisico tussen aluminium en composieten bracht drastische verschillen aan het licht, waarbij 25% van de impactors leidde tot schade die niet met het blote oog op composieten was waar te nemen. Dit is indicatief voor óf superieure weerstand ten opzichte van impactschade voor composieten, óf de mogelijke aanwezigheid van interne schade, wat additionele non-destructive inspection (NDI) vereist. Volgend op deze bevindingen is het besluitvormingsmodel toegepast voor een specifieke case: impactschade op een outboard flap. Het model identificeerde vijf haalbare opties. Bij evaluatie bleek dat twee opties domineerden als beste opties in het globaal zoekalgoritme, op basis van de eerder genoemde besluitvormingscriteria. Het evalueren van de vijf opties, met inachtneming van de twee grote stappen in het besluitvormingsproces die eerder zijn toegelicht, nam aanmerkelijk minder tijd in beslag dan de verscheidene dagen die het daadwerkelijk uitgevoerde proces in beslag nam. Daarnaast gaf het model aan wat de twee minst geschikte opties waren voor het geëvalueerde scenario. In het daadwerkelijke uitgevoerde proces werden ook deze opties serieus overwogen door de besluitvormer, wat aantoont dat een gebrek aan kwantitatieve analyse in de praktijk kan leiden tot suboptimale besluiten. Uiteindelijk zijn de genoemde methodes toegepast in de ontwikkeling van een besluitvormings-tool genaamd Airmedt (Aircraft Maintenance Evaluation and Decision Tool). Het doel van deze tool is om de daadwerkelijke toepassingsmogelijkheden van het onderzoek te demonstreren. In zijn huidige vorm staat de tool op zichzelf, en is in staat om reparatie opties te evalueren indien de randvoorwaarden van het scenario bekend zijn.. Voor toekomstige implementatie kan het besluitvormingsproces (deels) geïntegreerd en geautomatiseerd worden, waarbij relevante stakeholders zoals de onderhoudsafdeling, het Operational Control Centre (OCC), Maintenance Control Centre (MCC) en externe partijen kunnen worden gekoppeld.

Het onderzoek toont het potentieel van het idee om aluminium data te gebruiken om het toekomstig onderhoud van composieten te ondersteunen, maar er zijn een aantal lessen voor toekomstig onderzoek. Het grootste probleem in dit onderzoek was niet het gebrek aan data, maar de gebrekkige (beschrijvende) kwaliteit van de beschikbare data. Een groot deel van deze data (bijna 75%) was niet bruikbaar omdat de omschrijving van de schade (inclusief de dimensies) incompleet was of geheel ontbrak. Dit bena-

drukt de noodzaak om meer detail in het verzamelen van data te stimuleren, omdat dit betere analyses ondersteunt en meer inzicht biedt voor toekomstige verbeteringen. Een ander aspect dat verbeterd moet worden betreft de aannames die gemaakt zijn om het risico van impactschade op composieten vliegtuigen te verkrijgen. Het modelleren van impactschade gaat uit van een bolvormige impactor en een vlakke plaat om de analyse te simplificeren, maar de kromming van vliegtuigstructuren en andere materiaalvormen kunnen een invloed hebben op de verkregen resultaten. Daarnaast zijn de consequenties van een impact uitgedrukt in directe reparatiekosten, maar een dynamische benadering voor risico-evaluatie kan leiden tot een breder perspectief op impactrisico's. Dit dynamische aspect kan ook worden meegenomen in het identificatieproces voor reparatieopties, zodat dit proces aangepast kan worden om de best- en worst-case scenario's te identificeren of zelfs te voorspellen, wat het mogelijk maakt voor de besluitvormer om snel te reageren op veranderingen.

Ondanks deze beperkingen, verkennen de methodes die in deze dissertatie zijn geïntroduceerd een unieke kans om het domein van composietonderhoud vooruit te brengen. Het gebruik van aluminium data om schade aan composieten te voorspellen verbetert de kennis voor toekomstig onderhoud aan composieten vliegtuigen, voor zowel de frequentie als de types van reparatie die moeten worden uitgevoerd tijdens de levenscyclus van een vliegtuig. De verkregen risico's kunnen worden uitgebreid naar andere toepassingen, zoals het vaststellen van ontwerp- en reparatielimieten aan vliegtuigstructuren, het prioriteren van inspectiegebieden en –frequenties, of zelfs het identificeren van specifieke risicobronnen rond een vliegtuig en het ontwikkelen van mitigatieplannen om de werkomgeving te verbeteren. De specifieke toepassing die in deze dissertatie is verkend is besluitvorming omtrent reparatie. De voorgestelde methode stelt de besluitvormer in staat om een beter overzicht van dagelijkse beslissingen te ontwikkelen. Deze beslissingen worden versterkt door een verbeterde identificatie van alle reparatie-opties en analyse van deze opties met gebruik van kwantificeerbare beslissingsfactoren. Dit draagt substantieel bij aan het verminderen van de tijd die nodig is voor besluitvorming, terwijl de onderbouwing en het begrip voor de selectie van een optie wordt verbeterd. Deze voordelen worden onderbouwd door de case studies die in dit onderzoek zijn uitgevoerd. De huidige uitdaging om composietonderhoud op grote schaal uit te voeren wordt rechtstreeks aangepakt door de betere beschikbaarheid van aluminium onderhoudsdata via een deductief-inductief proces te gebruiken. Dit zorgt voor verbetering van de toekomstige onderhoudspraktijk.

NOMENCLATURE

AHP Analytical Hierarchy Process

Airmedt Aircraft Maintenance Evaluation and Decision Tool

ATA Air Transport Association

BDT Boolean Decision Tree

BVID Barely Visible Impact Damage

CFRP Carbon-Fibre Reinforced Plastics

CODAMEIN Composite Damage Metrics and Inspection

CP Compromise Programming

DSS Decision Support Systems

DTL Damage Threshold Load

EASA European Aviation Safety Agency

ELECTRE Elimination and Choice Expressing Reality

FAA Federal Aviation Authority

FC Flight Cycle

FEM Finite Element Model

FOD Foreign Object Debris

GUI Graphical User Interface

HTML Hypertext Markup Language

ICAO International Civil Aviation Organisation

IFB Initiation of Fibre Breakage

ISO International Organisation for Standardisation

IT Information Technology

KM Knowledge Management

MCC Maintenance Control Centre

MCDM Multi-Criteria Decision-Making

MIDAS Model Impact Damage on Aircraft Structures

MIDAS-C Modelling Impact Damage on Composite Aircraft Structures

MIDAS-M Modelling Impact Damage on Metal Aircraft Structures

MRO Maintenance, Repair and Overhaul

NHPP Non-Homogeneous Poisson Process

OAM Original Aircraft Manufacturer

OCC Operational Control Centre

PROMETHEE Preference Ranking Organisation Method for Enrichment Evaluation

QI Quasi-Isotropic

ROI Risk of Impact

RP Renewal Process

SRM Structural Repair Manual

TOPSIS Technique for Order of Preference by Similarity to Ideal Solution

UML Unified Modelling Language

USGAO U.S. Government Accountability Office

WSM Weigthed Sum Method

CONTENTS

1

INTRODUCTION

1.1. RESEARCH CONTEXT

The use of composites in commercial aircraft structures has increased with the introduction of the Boeing 787 and Airbus A350. The previous generation of wide-body aircraft, such as the Boeing 777 and Airbus A330, has largely been manufactured with aluminium as the main material [1]. An analysis by the U.S. Government Accountability Office (USGAO) in coordination with the Federal Aviation Authority (FAA) revealed that aircraft from the 1990s used composites for less than 16% of their structural weight. In contrast, the Boeing 787 and Airbus A350 increased the use of composite to 50% and 53% respectively [1–3]. Original Aircraft Manufacturers (OAMs) base their selection of materials on a set of structural performance requirements. On the one hand, composites help to meet some of these requirements by enabling structures to be light-weight, corrosion-resistant, and able to be moulded into complex optimised shapes [4]. On the other hand, composite structures are prone to internal damage due to impact and moisture ingress [4]. Fatigue resistance is also a requirement imposed on aircraft structures, but the capabilities of composites in that regard are still debated in the literature [1–4]. Nevertheless, even with the potential drawbacks of composites, their application is expected to grow in the future due to the pressures of weight reduction and increasing fuel efficiency [3, 4].

As composite aircraft replace ageing aluminium aircraft, there will be increased demand for maintenance on composite structures. Recent market research conducted by Airbus estimated that there were more than 21,400 aircraft (passenger with ≥ 100 seats, freight with > 10 tonnes) in service at the beginning of 2018 [5]. With 4.4% annual growth, this study predicted that the in-service fleet size will more than double by 2037, reaching nearly 48,000. A further breakdown estimated that nearly half of the fleet from 2018 will be replaced by new aircraft over that period [5]. OAMs are dedicated to expanding the use of composites not only to their latest generations but also to the previous generations, by redesigning wings, airframe, and fan blades [6]. As a result of this growing number of aircraft with composite material, it is important for Maintenance

Repair and Overhaul (MRO) organisations to be well equipped for the most common repairs.

One of the weaknesses of composites mentioned above is their susceptibility to impact [4]. Observing aircraft of use from the previous generation, and using significant amount of damage data Chen et al. indicated that more than 50% of all aircraft structural damage (such as dents, delaminations, and holes) were caused by impact [7]. This has been validated by the industry data utilised in this doctoral research, where 54% of damage on an aluminium aircraft fuselage is caused by impact. The two generations of aircraft differ in size, but they have the same wide-body fuselage shape and operate under similar conditions [8]. A high occurrence of maintenance due to impact is expected for composite aircraft as well, given the similarities in shape and operations between the two types of aircraft.

However, impact damage prediction and repair decision-making for composites are inadequate due to limited operational data. The aluminium wide-body aircraft such as the Boeing 777 have been in service since 1995 [1, 2], providing a large set of historical data concerning impact frequency and severity. Conversely, composite wide-body aircraft were introduced in the early 2010s [1, 2]. The life-cycle of a typical passenger aircraft ranges from 20-30 years [9]. Considering the young average age (3.5 years [10]) of composite aircraft in current operations, the accrued dataset on damage occurrences is relatively small, especially when these datasets are not gathered collectively but by individual operators and MRO organisations. Therefore, it is not possible to build a repair decision-making model for composites without a large dataset of damage. In order to adapt to the lack of sufficient operational data for composite repair decision-making, this research addresses the two following core research questions:

1. How can the gap in composite damage data be augmented using existing historical damage data from older generations of aircraft?

2. How can the composite maintenance decision-making process for impact damage be performed, while being substantiated by the historical damage data and satisfying operational constraints?

1.2. RESEARCH METHODOLOGY

The lack of data gathered over the lifetime of a composite aircraft is a hindrance to defining a comprehensive maintenance decision-making process. Additionally, the majority of the decisions in airlines and MRO organisations are motivated by operational constraints [11], but the historical data is not used to quantify recurring future damage and the effectiveness of the repairs. Therefore, the challenge to be addressed is two-fold: estimate impact damage and risk of impact on composite structures, and develop a repair decision-making model that accounts for operational constraints and the lack of historical data for repair option selection. Figure 1.1 summarises the methodology discussed in Section 1.2, including the different objectives to address the two-fold challenge. The research contributes to the development of a repair decision tool framework for composite structures.

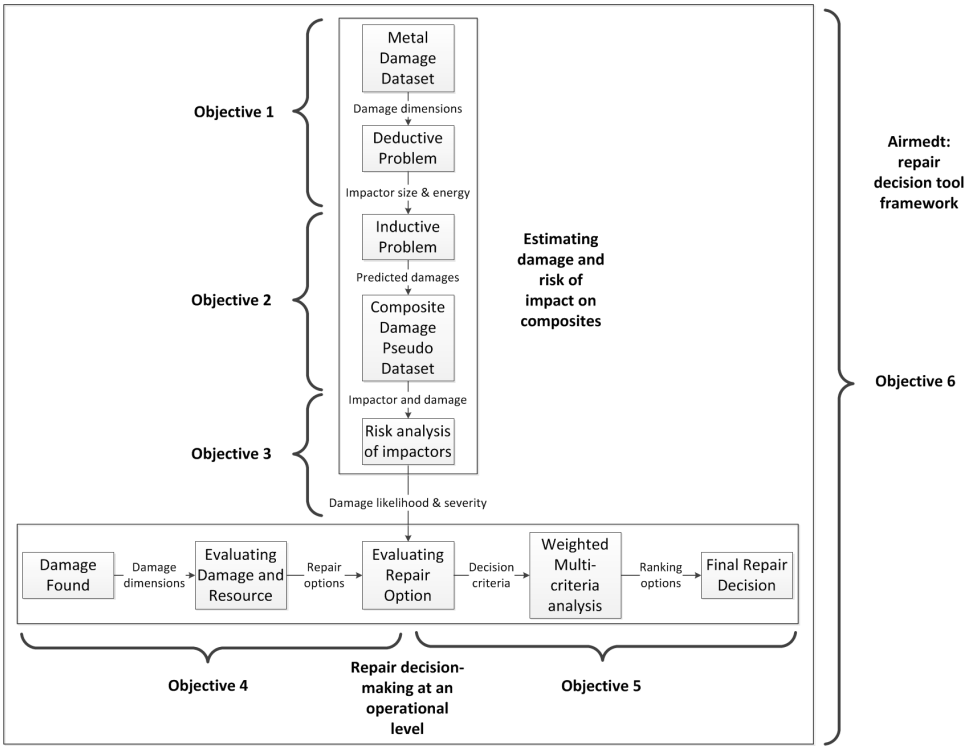

Figure 1.1: Research methodology and contribution

1.2.1. ESTIMATING DAMAGE AND RISK OF IMPACT ON COMPOSITES

To counter the lack of operational damage data for composite aircraft, this dissertation will use aluminium damage data. The core assumption is that both aircraft generations are of similar shape and are operating similar flight cycles in the same conditions, so the damage source can be assumed to be very similar. The shape of both generations of aircraft is cylindrical with comparable diameters. For example, the Boeing aircraft went from 6.20m for the 777 to 5.77m for the 787, and the Airbus aircraft went from 5.64m for the A330 to 5.97m for the A350 [8]. The change in barrel diameter between generations for both aircraft manufacturers is no more than 7%. In terms of similarity of operations, both generations of these wide-body aircraft are used for long-haul routes [12] with a range of 14,000km or more [13]. Therefore, this assumption enables the use of aluminium data to deal with future composite damage, given that the material properties are taken into account.

Aluminium and composite are fundamentally different materials. Aluminium has long been a staple material in aviation due to a vast collection of alloys that are applied for specific purposes. For instance, the 7xxx series alloy is used for high strength and the 2xxx and 6xxx series alloys for damage tolerance [14]. Despite the many custom aluminium alloys, the isotropic nature of the material means that its performance is uniform throughout, hindering directional optimisation. This has led to the rise of compos-

ites in aviation. Carbon-Fibre Reinforced Plastics (CFRP) used in the latest generation aircraft contain continuous fibres supported by a matrix material [3]. These brittle unidirectional fibres are oriented at different angles throughout the sequence of layers in the composite panels to provide specific tensile and compressive properties, making the panel anisotropic. Due to the differences between aluminium and CFRP, an analytical model capable of estimating impact damage for both materials is needed before the risk of potential impact events can be assessed.

The process of converting metal to composite damage can be separated into two problems: deductive and inductive. The deductive problem infers an impactor (size and energy) using the impact damage dimensions (length, width, and depth) on a known structure. The inductive problem models impact on a structure for a given impactor to estimate the final damage dimensions. A model has been developed named Modelling Impact Damage on Aircraft Structure (MIDAS) with two variants, one for metal structures (MIDAS-M) and another for composite structures (MIDAS-C) [15]. The purpose of using MIDAS is to identify the set of impactors and their characteristics that have historically damaged wide-body aircraft. These impactors are obtained from MIDAS-M by combining the known aluminium skin properties and the damage dimension data of a Boeing 777 fleet. Then the predicted impactors are used as inputs to induce damage onto a defined composite carbon-fibre reinforced plastic (CFRP) plate, and create a composite damage pseudo dataset. The conversion process is summarised as objectives 1 and 2 as indicated in Figure 1.1.

1. Deduce the impactor characteristics (size and energy) based on the dent dimensions (length, width, depth) on aluminium structures
2. Induce the damage onto composite structures to predict the damage dimensions (length, width, depth) and damage type, to create a composite pseudo damage dataset

Risk analysis of the deduced and induced impact events requires two pieces of information: likelihood and consequence. The challenge in practice is that the likelihood of an impactor (of a particular size and energy) striking an aircraft is not known. Yet, the likelihood of a particular damage can be obtained from the damage data based on the rate of occurrence. However, if the original impactor cannot be linked to a damage then the likelihood of the impactor cannot be easily obtained. The consequence of an impact is considered in terms of the type of maintenance required to repair the damage. A low-consequence damage would require no repair action or at most a temporary repair. Conversely, a high-consequence damage requires a more intensive permanent repair action. As established, MIDAS-M can deduce an impactor from a known damage dimension. Therefore, if the maintenance consequence of an aluminium damage is known through Structural Repair Manuals (SRM) limits, then by association the consequence of a deduced impactor striking an aluminium structure is also determined. Composite structures will also experience low- and high-consequence damage. Thus to quantify the consequence of the same deduced impactor striking a composite, the impactor is associated with the induced damage dimension. Through this conversion process the consequence of an impactor is determined. Combining consequence with

likelihood, the risk the impactor poses is quantified. Following the output of objectives 1 and 2, the risk analysis objective is formalised as:

3. Obtain the likelihood and consequence of impact events for the composite pseudo damage dataset, to inform the decision-making evaluation of repair options

The block of work titled "estimating damage and risk of impact on composites" in Figure 1.1 combines the deductive-inductive process with risk analysis. This research uniquely informs future maintenance challenges for composite aircraft, enabling MRO organisations to forecast and prioritise the repairs they can expect, and how they effect their daily operations. The direct application of the stated objectives is in the field of maintenance decision-making, using the likelihood and consequence as an indicator for how often repairs will have to be conducted on a composite aircraft.

1.2.2. REPAIR DECISION-MAKING AT AN OPERATIONAL LEVEL

Once a damage is detected, the challenge for an MRO is to choose the best repair option within a set of operational constraints. The steps of decision-making are not formalised in industry. Instead, the process involves several stakeholders, each with their own priorities, coming to a consensus through discussion [11]. Furthermore, the comparison of options is often quantified in terms of cost or downtime, but the durability of the structure is considered only as a qualitative factor. To address this informal approach to decision-making, the block of work titled "repair decision-making at an operational level" in Figure 1.1 has two objectives:

4. Identify all feasible repair options for a structural damage, constrained by operational factors
5. Evaluate the repair options based on decision criteria and quantitatively compare the alternatives to select the best option

First, to identify the repair options the operational constraints have to be clearly defined. A list of all repair options, as well as the associated constraints that dictate their feasibility, are defined in consultation with an MRO. These constraints are transformed into simple Boolean factors. Based on the setting of these factors, an option is either kept or eliminated [16–19]. Once all operational Boolean factors are set, the maintenance scenario is defined with a list of all feasible repairs. Typically, most Multi-Criteria Decision-Making models assume that the alternatives are already identified. However, in practice rarely do maintainers have the means to clearly organise all operational constraints to identify their options. This research uniquely contributes to the maintenance decision-making process field by explicitly introducing a systematic option identification step.

Second, to evaluate the feasible repairs a quantifiable set of criteria needs to be established; these include survivability, cost, and downtime [20]. Survivability is the cumulative probability that a part will survive beyond a specified time t_0 [21]. In the case of this research t_0 starts from the point of first repair action after damage. This criterion will be based on the historical data, or in the case of composites, the pseudo data.

Cost is composed of the expenses or losses of revenue directly related to the repair of an asset. Downtime is the amount of time the asset is not producing revenue due to a repair. All the options are compared to each other quantitatively based on these criteria. With a weight assigned to each criterion, an aggregated score is calculated for each option, assisting the decision-maker in selecting the final repair [22–25]. Furthermore, the multi-criteria evaluation has been expanded upon in this study introducing a novel global weight search algorithm. A thorough search of all weight cases identifies options that would never be considered the best, and thereby reducing the number of alternatives that should be considered.

1.2.3. AIRMEDT: REPAIR DECISION TOOL FRAMEWORK

The estimation of impact risk for composites combined with the repair decision-making provides a holistic framework as depicted in Figure 1.1 for maintenance of composite aircraft. The individual methods developed to address the objectives, independently contribute to the state-of-the-art in their respective fields. However, to put the research into practice, the end-user requires a tool that is intuitive to use and easy to implement into operations. This leads to the final objective that encompasses the research as a whole:

6. Design and build a maintenance decision-making tool that incorporates the research theoretical methods, to be used in daily operations once implemented

The broad field of Knowledge Management (KM) is the foundation on which the decision-making tool is developed. KM is the process that leverages knowledge to improve an organisation's operational performance [26, 27]. With the increased use of information systems, a subset of KM called e-Maintenance has gained relevance in recent years [28, 29]. Decision Support Systems (DSS) is an e-Maintenance framework, that exploits the knowledge in a network of information systems to gain operational advantage. The fundamentals of DSS as set by Keen [30] directly influenced the design and build of the maintenance decision-making tool, Airmedt (**Air**craft **M**aintenance **E**valuation and **D**ecision **T**ool).

Airmedt has been developed for maintainers to use in their daily operations. It is currently a standalone application accessible via Internet browser, or as an app on smartphones and tablets. The prototype is designed to 1) present unstructured problems in an understandable manner, 2) coordinate different models and techniques together, 3) be intuitive to use by anyone with basic knowledge in computers and maintenance, and 4) be flexible for future modifications. Objectives 4 and 5 directly addresses the unstructured nature of decision problems in daily operations, but Airmedt needs to also visually present the results of the analysis. As for the coordination of different models and techniques, these are explicitly shown in Figure 1.1 by the connections formed between the different steps of the research methodology. To ensure that Airmedt is intuitive to use, the tool is designed to be interactive and the maintenance shop has been involved to inform the final requirements from a user perspective. Lastly, the architecture of Airmedt has been build such that modules can be easily built and integrated into the existing tool to perform additional functions in the future. Although Airmedt is a prototype, it provides a vision for implementing the research methodology into operations.

1.3. OVERVIEW OF DISSERTATION

For ease of navigating the dissertation, please refer to Figure 1.2. Following the introduction, Chapter 2 uses the aluminium damage data to deduce the set of impactors that have historically struck a wide-body aircraft. A risk assessment is conducted on the deduced impactors, quantifying their likelihood and maintenance consequence. Next, Chapter 3 demonstrates the process of combining deductive and inductive problems to predict future damage on a composite aircraft. Once again, the impactors are assessed for the risk they pose on both aluminium and composite structures. In Chapter 4 a decision-making model is proposed that relies on historical damage data and operational settings to identify and evaluate repair options for a damaged composite structure. Based on the overall methodology Chapter 5 culminates in the presentation of the Airmedt tool, developed to put the decision-making model into practice and exploring future implementation. Finally, Chapter 6 reviews the findings of the dissertation, stating the main conclusions and recommendations for future research.

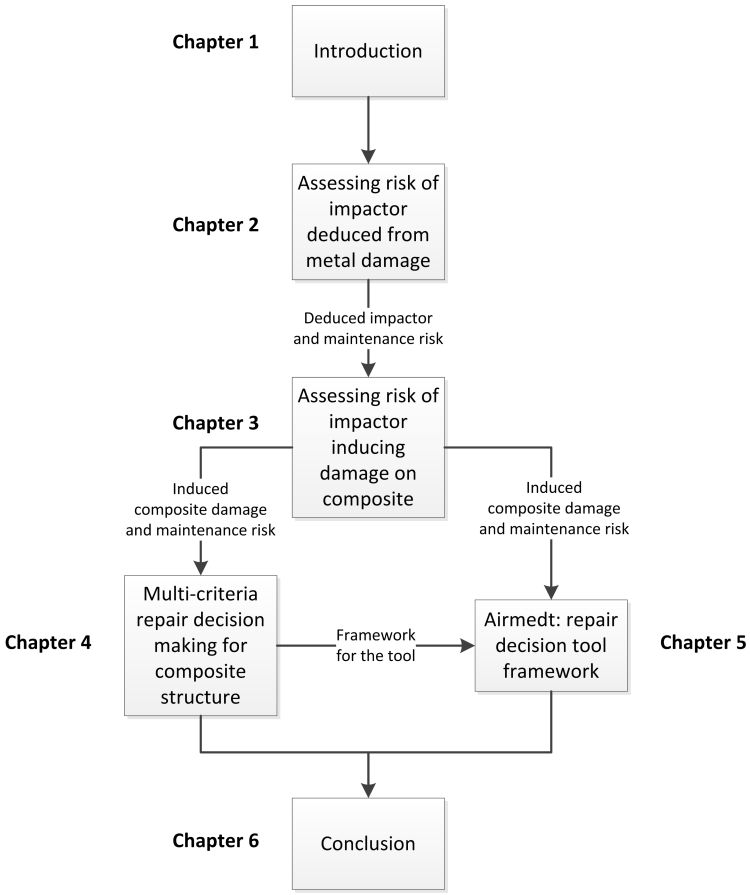

Figure 1.2: Overview of dissertation

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2

ASSESSING RISK OF IMPACTOR DEDUCED FROM METAL DAMAGE

This chapter uses an analytical impact damage model to deduce the characteristics (size and energy) of an impactor striking an aircraft structure, based on historical aluminium damage dimension data. The study addresses the current state-of-the-art concerning the characterisation of the impactor and the associated risk posed to aircraft. The risk is currently only known in general terms to aircraft operators, who have limited analytical means to estimate event likelihood and consequence. The model is applied in a case study using 120 fuselage dent damage dimensions (length, width, and depth) from a Boeing 777 fleet. This process identifies the potential threats that any aircraft of similar size and operations would experience. Hence, the output of this chapter leads to predicting future impact and associated damage for composites.

Parts of this chapter are under review for publication [1]

2.1. INTRODUCTION

Federal Aviation Authority have conducted surveys to capture the variability of non-wildlife impactor material type and size [2]. Such surveys of hazardous debris around an aircraft can find a collection of potential impact threats, but the likelihood that these impactors strike an aircraft is not known. Moreover, the relation between impactor and the resulting damage is also unknown, because human inspectors can observe the final damage, but often cannot identify the original source. Therefore, to understand the types of impactor that would strike an aircraft, this study proposes that the characteristics of an impactor (radius and energy) can be deduced from a set of structural damage dimensions and material properties of the damaged structure.

Two crucial sources of information that MRO organisations hold are 1) structural damage data (dent dimensions, time of damage, area on structure) of aircraft and 2) the Structural Repair Manual (SRM). The risk posed by an impactor is based on a combination of the likelihood it will strike (with a specific energy) and the consequence of that event. The likelihood is obtained from the aircraft structural damage dataset, while the consequence is defined as minimum repair action in the SRM. The repair action is quantified in terms of cost based on the technical report "The economic cost of FOD to airlines" [3]. To predict impactors that pose a risk, an analytical model has been developed by Massart [4] that uses damage dimensions as input. This model is termed MIDAS-M, which stands for Modelling Impact Damage on Metal Aircraft Structures.

MIDAS-M combines elements of impact damage modelling methods proposed by Simonsen and Lauridsen [5], Abrate [6], Shivakumar *et al.* [7], Liu *et al.* [8], and Lee *et al.* [9]. The developed model estimates the response of the plate to an impact event, resulting in elastic and plastic deformation. By simulating multiple impact events on a defined plate for a range of impactor radii and energies, MIDAS-M obtains a vast set of feasible damage. Finally, the actual damage dimensions found in the maintenance dataset are correlated with the simulated damage of MIDAS-M to deduce the corresponding impactor radius and energy.

The remaining content of this chapter consists of six sections. First, the theoretical background behind the development of MIDAS-M is established. Then, a sensitivity analysis of MIDAS-M is presented using computational (FEM) model developed based on data from literature (Fagerholt *et al.* [10]). With the understanding of the range of validity, a case study is set up outlining the maintenance data used, assumptions for the impact event, the process of MIDAS-M, and the approach for risk assessment of impactors. The purpose of the case study is to demonstrate the process of predicting the impact threats and subsequently quantifying the risks they pose. As such, the predicted impact threats from MIDAS-M are presented, followed by risk assessment results. Based on the findings some of the core limitations of the model in this particular case study are discussed. Finally, the conclusion section addresses the main findings of the research and identifies several avenues for future research.

2.2. METAL IMPACT MODEL (MIDAS-M) SUMMARY

MIDAS-M has been developed to model impact damage on metal plates. The structural response of metals during an impact has been explored by various researchers in litera-

ture [6, 11–14]. For details on the development process of the analytical model MIDAS-M the reader is advised to refer to the thesis by P. Massart [4], the specific equations can also be found in Appendix A. This section distils the theory behind the functionality of MIDAS-M, and discusses the key assumptions:

1. Impact event is a boundary dependent quasi-static event

2. The deformation shape consists of three regions: indentation, transition, plate deflection

Typically impact events are characterised by a superposition of local indentation and a global plate deflection [15–19], both associated with different dependencies influencing the final response. For instance, local response is considered to be both boundary- and time-independent. Thereby, the deformation at the area of contact (with radius of R_c) is directly influenced by the geometry of the indentor. Whereas, the global plate deflection is boundary-dependent, largely influenced by type of support conditions and the geometry of the plate itself. Therefore, to simplify the characterisation of the impact event in MIDAS-M, the impact event is assumed to be a boundary-dependent quasi-static event.

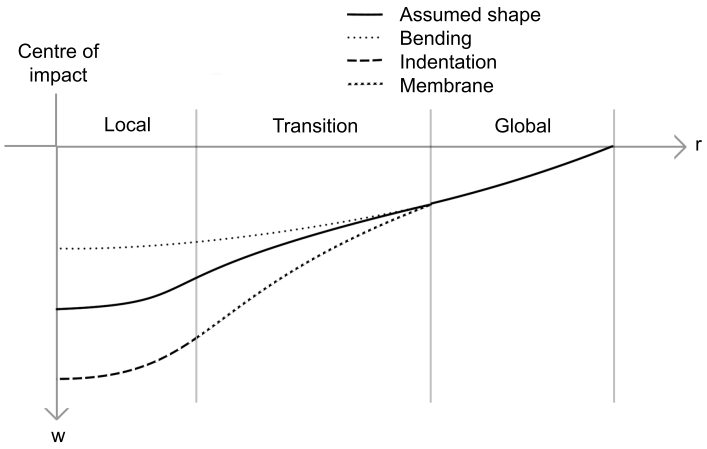


Figure 2.1: Plate deflection during an impact event based on weighted average of bending and membrane limit case solutions [4]

MIDAS-M introduces a novel transition region within the theoretical superposition of local indentation and plate deflection. During the development of MIDAS-M it was determined that the super-positioning approach was simplifying the overall shape of the plate, causing errors. It is important to capture the flexible nature of metal targets to reduce these errors [10, 20]. While the local region continues to follow the geometry of the impactor in the form of an indentation, the membrane approach developed by Simonsen and Lauridsen [5] and Lee *et al.* [9] models the shape for the rest of the plate at near penetration. This membrane approach validity increases when the deflection is

greater than the thickness of the plate, and the global plate deflection theory [21, 22] is valid for bending of small deflections. Therefore, the transition region averages the contribution of membrane approach and plate deflection theory to obtain a more realistic deformation shape (see Figure 2.1, where w is deflection, and r is plate radius).

2.3. FEM VERIFICATION OF MIDAS-M

The analytical model MIDAS-M has been verified using a Finite Element Model (FEM), which is validated by experimental results from Fagerholt *et al.* [10]. The dynamic nature of the impact event is modelled in Abaqus using a Dynamic/Explicit step [23]. The computational model provides detailed representation of real impact tests at the cost of high run-time due to both the required mesh size and time marching scheme. This section covers some examples of the verification conducted by P. Massart [4], for more details on the computational model and additional examples of verification, the reader is advised to refer to the thesis. Nevertheless, by comparing a collection of impact cases with the analytical model and the computational model, the MIDAS-M range of applicability is determined. This establishes the extent to which maintenance damage dimension data can be used to calculate the impactor characteristics.

2.3.1. REFERENCE CASES FOR VERIFICATION

The verification of MIDAS-M with respect to FEM was conducted based on the specifications of a wide-body aircraft. The rectangular plate is simplified to the dimensions of typical frame and stringer pitch. These dimensions were obtained from CODAMEIN (Composite Damage Metrics and Inspection)[24] and shown in Table 2.1. The report also provided Al2524 as the primary material for Boeing 777 aircraft fuselage, the relevant properties of which are described in Table 2.2.

Table 2.1: Range of wide-body aircraft fuselage dimensions[24]

Stringer pitch (mm)	Frame pitch (mm)	Skin thickness (mm)
150-250	457.2-533.4	1.0-2.6

Table 2.2: Material properties of Al2524 [25, 26]

Material	σ_y (MPa)	σ_u (MPa)	ε_u (%)
AL-2524	275.8	413.7	21

For the verification tests four variables (related to plate and impactor characteristics) are controlled as summarised in Table 2.3: plate size, plate thickness, impactor radius, and impact energy.

Table 2.3: Range of parameters for sensitivity analysis

Plate width (mm)	Plate thickness (mm)	Impactor radius (mm)	Impact energy (J)
200, 300	1, 1.5, 2, 3, 4	10, 25, 75	5, 10, 25, 50

2.3.2. SENSITIVITY ANALYSIS OF IMPACT EVENT

MAXIMUM FORCE AND DISPLACEMENT

The first set of sensitivity analysis conducted verifies how well MIDAS-M reproduces the maximum force and displacement predictions compared to the FEM results. The FEM is based on literature experiments [10] and is a representative comparison for the analytical model. Two tests are conducted for MIDAS-M to analyse its sensitivity with respect to all four test parameters. Verification test 1 varies the plate width for a fixed plate thickness (2mm) and obtains the response to different impactor radius and energy (Table 2.4). Then for verification test 2, the plate thickness is varied for a fixed plate size (200mm) and impactor radius (25mm), tested at 5, 10, 25, and 50J (Table 2.5). The experimental setup by Toso and Johnson [27] in testing for runway debris, set the ranges for impactor radius and impactor 10-25mm and 20-140J respectively. The sensitivity analysis will also check for larger impactors and lower energies to verify the overall response trend [4].

Table 2.4: Verification test 1 - Variation of impactor and plate size

Test 1

Fixed variable		Independent variables	Dependent variables
Plate thickness	2mm	Plate width	Force (kN)
		Impactor radius	Displacement (mm)
		Impact energy	

Table 2.5: Verification test 2 - Variation of plate thickness

Test 2

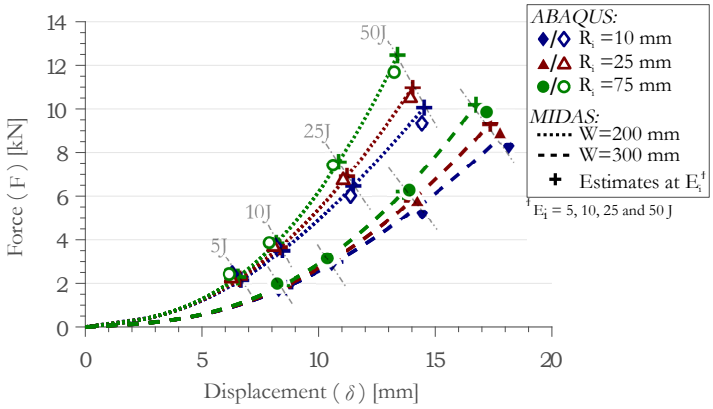
Fixed variables		Independent variables	Dependent variables
Plate width	200mm	Plate thickness	Force (kN)
Impactor radius	25mm	Impact energy	Displacement (mm)

SENSITIVITY RESULTS FOR MAXIMUM FORCE AND DISPLACEMENT

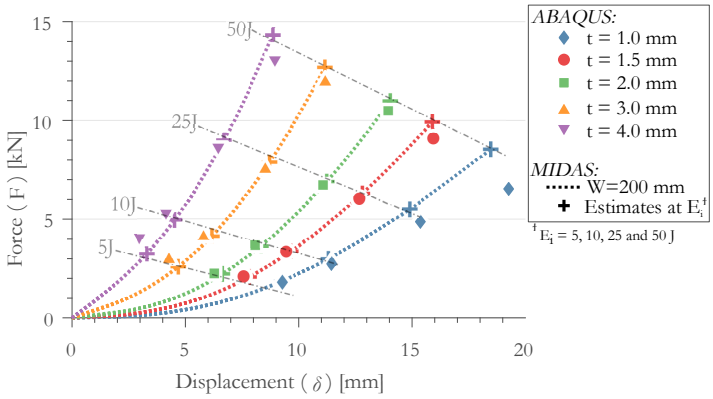
Figure 2.2a shows response to impact for two different plate sizes, where a wider plate has larger displacements. The bending stiffness of the plate decreases with the increasing plate size, leading to more flexing of the plate. With increasing energy both maximum force and displacement increases. However, for a given energy, a larger impactor reduces maximum force but increases displacement. Due to the larger contact area of the impactor, the impact energy is more widely distributed leading to lower peak force, and there is more bending contribution than membrane which leads to higher displacement. Figure 2.2b shows the effect of plate thickness, where due to the higher bending stiffness of thicker plates the displacement is smaller and maximum force is higher than that of thinner plates.

The predicted maximum force and displacement values of FEM and MIDAS-M shown in Figure 2.2 are in good agreement with each other. The errors in majority of the cases remain low, but increases with higher energies while still remaining less than 10%. The largest errors are for a thin plate of 1mm thickness at energy levels of 25 and 50J. Upon

further investigation, the error is thought to have been caused by excessive element distortion in the FEM model at the boundary, which MIDAS-M does not include.



(a) Variation of impactor and plate size



(b) Variation of plate thickness

Figure 2.2: Comparison of MIDAS with FEM simulations [4]

DEFORMATION SHAPES

The final shape of the plate is the second aspect to be verified. To do so, the deformation at maximum force, and the final residual permanent deformation are modelled. Figure 2.3 shows the effect of plate thickness on the deformation shape for a fixed plate width of 200mm, energy of 50J, and 25mm impactor radius. The shape results are not well reproduced for thicker plates (t = 3-4mm) compared to thin plates. The error is greater still for plastic radius estimates. Plastic radius and permanent dent depth exhibit highest errors in terms of percentage for low energy impact. However, it should be noted that at energy <10J, the small scale of deformations are too impractical to be detected with visual inspection.

Figure 2.4 and 2.5 show deformation shape for a fixed plate size of 200mm and thickness of 2mm, at varying levels of impact energy (5, 10, 25, 50J). The plate in Figure 2.4

is struck by an impactor of radius 10mm, while in Figure 2.5 it is impacted by a larger 75mm impactor. These two figures demonstrate the shift in contact radius depending on the impactor radii, thereby changing the shape.

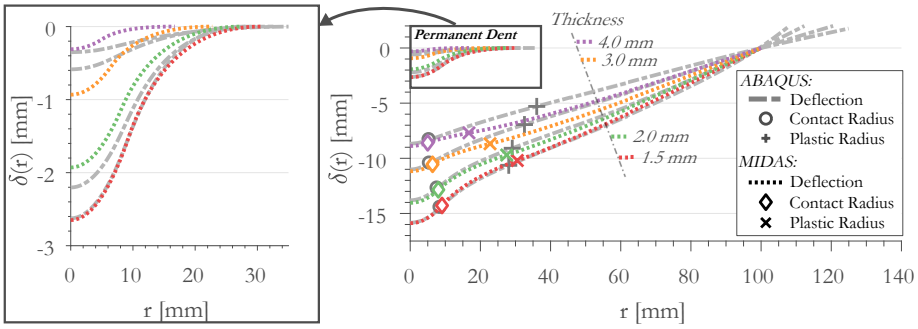


Figure 2.3: Maximum and permanent deformation of MIDAS-M and FEM (plate width 200mm, thickness 1.5/2/3/4mm, impactor energy 50 J, impactor radius 25mm) [4]

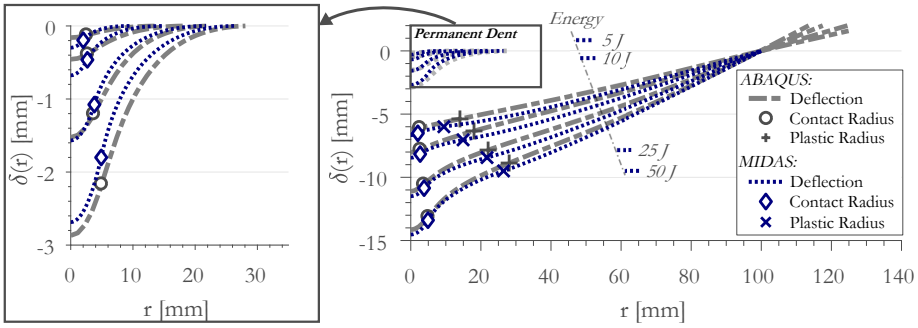


Figure 2.4: Maximum and permanent deformation of MIDAS-M and FEM (plate width 200mm, thickness 2mm, impactor radius 10mm, impactor energy 5/10/25/50J) [4]

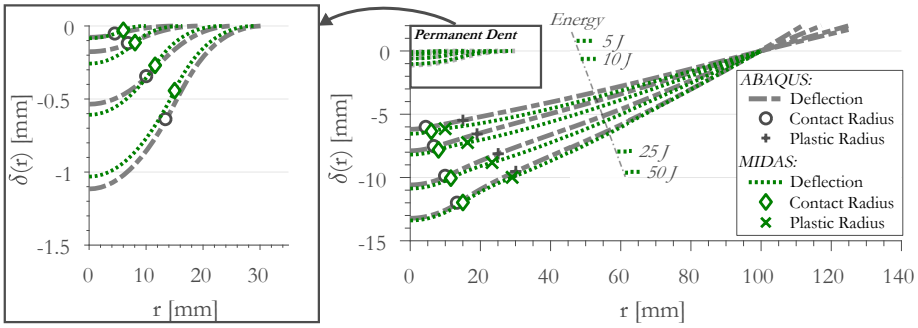


Figure 2.5: Maximum and permanent deformation of MIDAS-M and FEM (plate width 200mm, thickness 2mm, impactor radius 75mm, impactor energy 5/10/25/50J) [4]

2.4. PROCESS OF DEDUCING AND ASSESSING THE RISK OF IMPACTOR

MIDAS-M has been developed to model impact events and verified against a FEM model. Now a case study is designed to use structural damage data from a major European carrier as an input for MIDAS-M to deduce impactors in a realistic scenario. The deduced impactors are used as input in the risk assessment for metal maintenance. Through this case study, the likelihood and consequence of impact on metal aircraft is quantified with respect to the deduced impactor.

2.4.1. CASE STUDY SET-UP TO DEDUCE IMPACTOR CHARACTERISTICS

STRUCTURAL MAINTENANCE DATA

The raw dataset of aircraft structural damage spans the period from 1999 to 2015, for a fleet of 97 aircraft. Due to the large size, the quality of the data being used for MIDAS-M has to be ensured in accordance with accuracy, consistency, and completeness criteria, as defined by Hazen *et al.* [28]. Accuracy measures how close to reality is the data, consistency is the adherence of data to same format and structure, and completeness is the proportion of necessary data that has values. The dataset was subject to an internal validation process at the carrier, which ensured the accuracy of the data logged, starting in late 2004. Hence, a time-span of 2005-2015 is chosen, which reduced the fleet size being analysed to 75 aircraft.

A strict format is enforced on the dataset to standardise the information gathered, and include the following fields required for MIDAS-M: ATA, sub-ATA, damage description, and damage dimensions (length, width, and depth). ATA and sub-ATA is a standard documentation system established by the Air Transport Association, consisting of a number of chapters referencing different components and structures of an aircraft. For instance, ATA 53 refers to the aircraft fuselage, and sub-ATA is an extension to specify sections of the aircraft fuselage. Using this referencing system the damage limits defined in the Structural Repair Manual can be found. The damage description field typically states both qualitative and quantitative information about the damage. Qualitatively, the data declares whether the damage is a dent, lightning strike, hole, etc. This case study considers only data that are described to be dents or dents with scratches, which constitute 60-90% of impact-related damage depending on the fuselage section. Quantitatively, MIDAS-M requires the exact dimensions of the dents in terms of length, width, and depth. All of this information combined will be the input for MIDAS-M, but the individual data items are not all perfect, requiring data pre-processing as described below.

The first and most pressing issue of the input for MIDAS-M is that there are elliptically shaped damage recorded in the maintenance data. However, the analytical deductive process requires circular damage as an input. The damage data is approximated to be a circle to compensate for the eccentricities of the damage shapes, by equating the area of the elliptical damage to that of an equivalent circle. Thereby, the area of the ellipse shape can be used to estimate the radius of the approximated circular damage.

$$\pi ab = A_{ellipse} = \pi r^2_{approx.} \tag{2.1}$$

$$\sqrt{ab} = r_{approx.} \tag{2.2}$$

Where,
a , is the semi-major axis of elliptical damage
b , is the semi-minor axis of elliptical damage
$r_{approx.}$, is the radius of approximated circular damage

An additional problem of using this dataset that spans a substantial time (2005-2015) is the lack of completeness. There are instances where not all fields of the data collection are filled. To counter this and recover as much information as possible, a cross-relational search is employed. For instance, it may be that the sub-ATA chapters is not recorded, but the ATA chapter and a keyword for the part is marked. By correlating the recorded data with other complete data, the sub-ATA can be deduced. After this pre-processing of data, 479 dents are confirmed across three sections of the fuselage.

Furthermore, a field that has a damage description still may not be complete due to missing values of the damage dimensions. All three measurements of length, width, and depth are required. Thus if any single parameter is missing then that particular damage instance cannot be used for MIDAS-M. In the end, after accounting for the dataset limitations, approximately 25% of the 479 confirmed dents are retained for analysis. In other words, a sample set comprising 120 impact events is used to estimate the impactor characteristics.

IMPACT EVENT ASSUMPTIONS

MIDAS-M can use actual aircraft dimensions to define the plate, but due to the confidentiality restrictions, any values directly provided by the SRM cannot be stated. Instead, the research project by EASA named CODAMEIN and values from literature will be used to give an overview of the materials and design for wide-body aircraft [24]. The information gathered will define two aspects of the plate setup: material properties and plate size. The ranges of these values are the same as the ones used in the computational model and can be found in Subsection 2.3.1.

There are practical restrictions in the way the simulations are run for the case study. One of these conditions is that the precise location of the damage is not always known. Damage are found and noted as being between two frames and two stringers, each with a different identification number. The record does not indicate how close to the edges (frame or stringer) the impact occurred. This leads to the first assumption during simulations which is that the impact will always occur in the centre of the plate.

The other practicality influencing the tests is the effect of the boundary conditions. A simply-supported assumption is expected to characterise the actual response of the plate to an impact event, with the stringers and frames acting as a pivot point for the plate. For higher fidelity, ideally the simulation would be running for a complete section of a fuselage, explicitly modelling pertinent frames and stringers. However, accounting for the additional structures at the boundary drastically increases computational time. With the current implementation of these two assumptions, the analytical model is simplified, reducing run-time.

As a final point, a yearlong survey conducted by FAA of an operating airport revealed that more than 60% of the reported Foreign Object Debris (FOD) were metal, with another 18% being rubber [2, 29]. Therefore, the model is developed with the assumption of metal impactors.

PROCESS OF MIDAS-M

There are two steps in the process of using damage dimensions as input to deduce and present the calculated threats: generate a contour map of all possible damage dimensions and plot the reference damage data to interpolate the impactor size and energy. The deductive problem will simulate multiple events of impact on an aluminium plate to create a contour map of all possible damage. Using the 120 sample damage data and the contour map the impactor radius and energy will be estimated.

First, the model runs simulations for multiple impactor radii (ranging from 1mm – 250mm) striking the aluminium plate. This produces a contour map of a wide range of impact events with their associated damage dimensions, as shown in Figure 2.8 in Subsection 2.5.1. On the one hand, the simulation shows that for a fixed impactor radius more severe damage is created with increasing energy, both in terms of damage depth and radius. The simulation continues for an impactor radius until it reaches penetration, producing the upper bound of the contour map. On the other hand, with an increasing impactor radius and fixed energy, the damage depth decreases but the damage radius increases. This trend is due to the larger contact radius between the impactor and the plate, leading to a shallower but larger damage area. The variation in impactor radii and energy generates a wide range of possible aluminium damage.

Second, the reference structural damage data is plotted onto the contour map to interpolate the impactor radii and energies of the dataset. It should be noted that to ensure confidentiality of the aircraft manufacturer and SRM design information, both the depth (δ) and the radius (R_p) dimensions are normalised as δ/t and R_p/R_0 respectively (t = thickness, and R_0 = half of the plate's smallest dimension). Each data point has a damage radius and depth, which are placed on a Cartesian grid of δ/t vs R_p/R_0 accordingly. Then based on the position of the data point relative to energy and impactor radius curves, the impact event values are interpolated. Essentially, the curves of the contour map act as a new coordinate system onto which the reference data is transformed.

In addition to the interpolation curves, the contour map includes the damage limits of the aluminium plate as stated in the SRM. These limits are also redefined in normalised form: maximum ratio of damage depth and radius $(\delta/t)/(R_p/R_0) = 0.2$ [30], and maximum depth $\delta/t = 1.98$. As a result, the low-consequence region satisfies both these limits, requiring temporary repairs at most.

2.4.2. IMPACTOR RISK ASSESSMENT

RISK ASSESSMENT FRAMEWORK

MRO organisations can quantitatively approach the risk posed by a particular impactor by following the 5-step Safety Risk Management Process established by the International Civil Aviation Organisation (ICAO) [31]: hazard identification, hazard probability, hazard consequence, risk assessment, risk control/mitigation. For this study the impactors are the hazard, identified by MIDAS-M using MRO structural damage data. The risk management process is re-contextualised for this case study as illustrated by Figure 2.6. Structural damage thereby serves as an input to obtain probability and consequence in terms of impactor. It should be noted that the scope explored here does not include the development of mitigation plans, but instead it is confined to providing the assessment necessary for MRO organisations to develop their own programs.

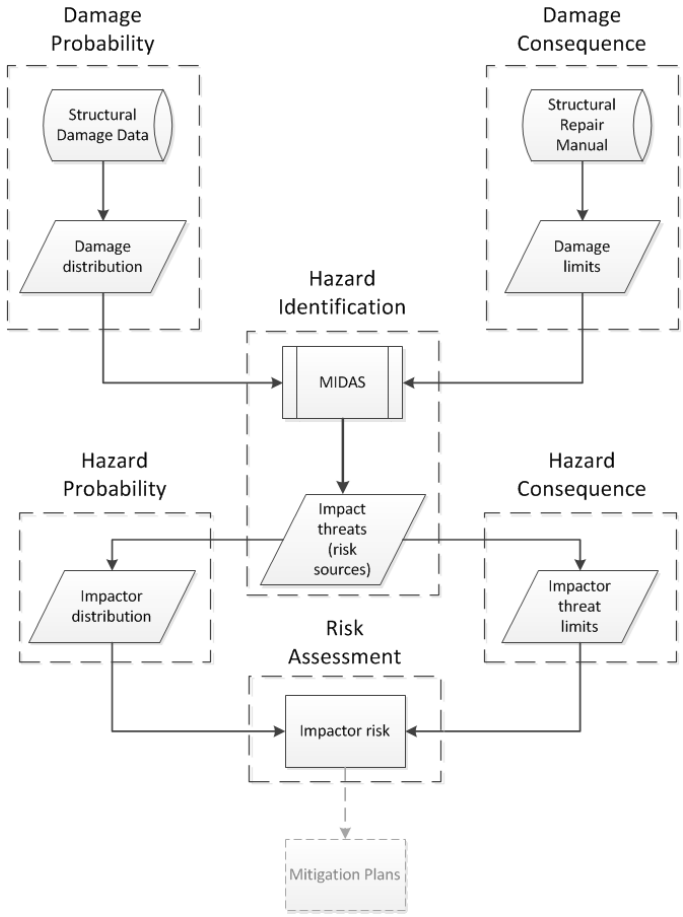


Figure 2.6: Process representation of the proposed approach towards impactor risk assessment, based on ICAO framework [31]

Once the impact threats are determined, the risk-based approach is applied. The definition of risk stated by the International Organisation for Standardisation (ISO) is the “effect of uncertainty on objectives” [32, 33] and is composed of four aspects: risk sources, potential events, consequences, and likelihood [33] (see summary after this paragraph). This study scopes the risk source to the impactor obtained from MIDAS-M. The potential events are represented as the risk source (in this case an impactor) hitting the aircraft with a specific size and energy. The consequence of an impact are the maintenance steps required after the event: no repair, temporary repair, or immediate permanent repair, each quantified with their own associated direct repair cost (see for example Dhanisetty *et al.* [34] and Chapter 4). Lastly, risk likelihood can be quantified directly in terms of rate of occurrence in the dataset. ICAO and ISO use "probability" and "likelihood" interchangeably, but in the context used by the two organisations they hold

the same meaning. The works of Chen *et al.* [30], use maintenance data to quantify the distribution of damage sizes in terms of stochastic processes. Following their approach the impactor size and energy gathered from MIDAS-M will be tested against common distributions: Weibull, normal, lognormal, and log-logistic.

Risk sources: single or multiple impact threats with an associated size and energy

Potential events: an object striking aircraft skin

Consequences: no maintenance required, temporary maintenance required, permanent (heavy) maintenance required

Likelihood: the statistical probability of an impact threat event

DETERMINING IMPACTOR RISK

The risk sources are deduced by MIDAS-M, but both the likelihood and consequence of the impact events need to be defined. The contour map from MIDAS-M shows the process of the deductive problem, but the calculated impact events can be presented directly on to the transformed coordinate system of impact energy vs. impactor radius.

The transformation of the MIDAS-M results creates a scatter plot of impact events, each with their impactor size and energy. The threat limit curve divides all possible events into two regions as seen in Figure 2.7: allowable damage (below the curve), non-allowable damage (above the curve). Essentially any impact threat in the allowable region is of "low-consequence" requiring temporary repairs at most, whereas the non-allowable region requires immediate permanent repair solution and is therefore considered "high-consequence."

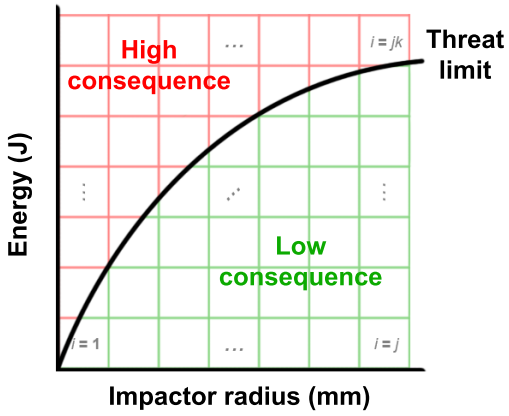


Figure 2.7: Impact threat radius and energy

Consequence in terms of repair cost can have a wide distribution according to the report "The economic cost of FOD to airlines" [3]. Cost consists of both direct repair cost (such as labour-hour, materials, and machining) and indirect cost (which includes delay or flight cancellation fee). A maintenance decision-making study on composite repairs (Dhanisetty *et al.* [34] and Chapter 4) determined that occurrences of indirect

Table 2.6: Direct repair cost distribution on aircraft skin damage [3]

Cost($)	Probability(%)
100	47.0
300	34.0
500	9.5
700	7.0
1,000	2.0
1,500	0.2
2,000	0.2
5,000	0.1
10,000	0.1
15,000	0.01

cost largely depends on when the damage is found rather than the damage severity itself. An example of low indirect cost is when the damage is found during an A-check, which typically lasts up to 24 hours, so there may be enough time to conduct a repair without disturbance to the network flight schedule. Conversely, if that same damage was found at the gate before push-back, this would lead to indirect cost in the form of a delay €100/min or even a cancellation, which for wide-body aircraft can range between €78,600 - €114,790 [35]. Therefore, due to this fluctuation of indirect cost uncorrelated with damage size, only direct repair cost will be considered. In Table 2.6, $300 with 34% probability is the biggest cost contributor with an expected value of $102. The expected cost of high- and low-consequence damage will be similarly determined based on their ratio in the deductive problem results.

The next aspect of risk to be quantified is the likelihood of a certain threat. For this step, the global space of impact threats in Figure 2.7 is discretised into a grid of $j \times k$ segments. The discretisation is applied so that the data points are gathered into consistent groups in terms of impactor characteristics. The likelihood of segment i is the ratio between number of threats in a segment ($n_{i,total}$) and total number of threats (n_{total}). The size of the segments can be flexible because it is dependent on the clustering of the results. If the segment is too small than the analysis will be too specific, leading to a large number of segments with very low likelihood. Conversely, if the segment is too big then the risk analysis is too general, few segments with very high likelihood. Hence, the motivation for the grid size is going to be iterative. The proportion of high- and low- consequence threats within a single segment are the ratios $\frac{n_{i,high}}{n_{i,total}}$ and $\frac{n_{i,low}}{n_{i,total}}$ respectively. As a result of the way the consequence and likelihood of a threat are defined, the general equation for risk of each segment i is as follows:

$$ROI_i = \left(C_{high}\frac{n_{i,high}}{n_{i,total}} + C_{low}\frac{n_{i,low}}{n_{i,total}}\right)\frac{n_{i,total}}{n_{total}} \tag{2.3}$$

Where,
i , is segment number
ROI_i , is the risk of impact for segment i
n , is the number of threats

C_{high} , is the cost of high-consequence
C_{low} , is the cost of low-consequence

Using Equation 2.3 the risk value for each segment is calculated. To provide a more pragmatic overview of the risk, three categories are created: Low, Medium, and High. The risk values of each segment are normalised using Equation 2.4. Then each risk category is given a range of normalised risk values: Low ($ROI_{i,norm} \leq 0.2$), Medium ($0.2 < ROI_{i,norm} \leq 0.6$), High ($0.6 < ROI_{i,norm} \leq 1$).

$$ROI_{i,norm} = \frac{ROI_i}{ROI_{max}} \tag{2.4}$$

2.5. RESULTS AND ANALYSIS

First, a contour map of all possible damage dimensions is generated, with the 120 sample data plotted to interpolate the impactor size and energy. The sample data is obtained from three different sections (A, B, C) of the aircraft fuselage. Then the independent histograms of expected impact energies and impactor radii are presented. Finally, the consequence and the likelihood of impact events are combined to produce a distribution of impact threat risk.

2.5.1. GENERAL CONTOUR FOR INTERPOLATING IMPACTOR RADIUS AND ENERGY

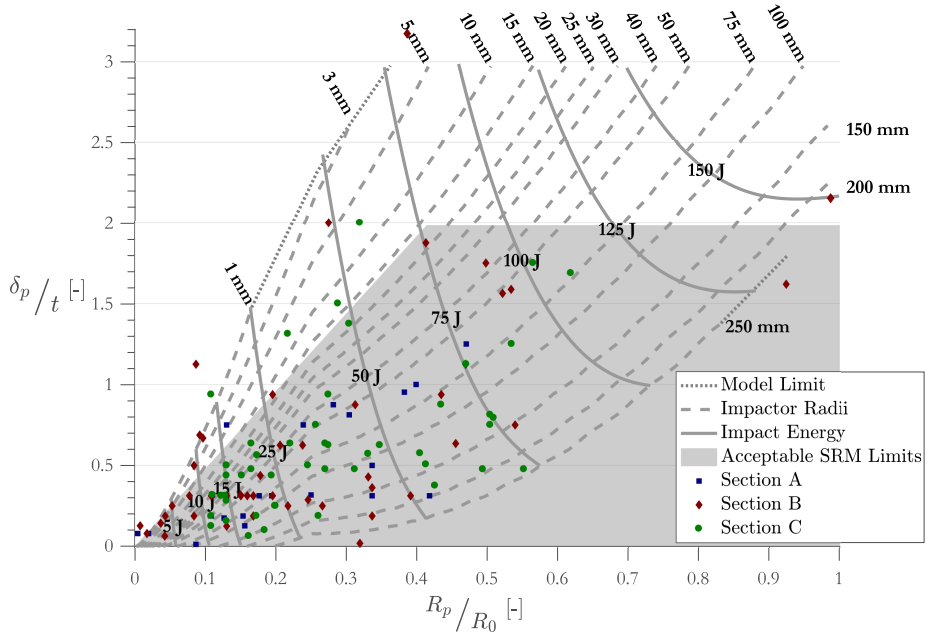
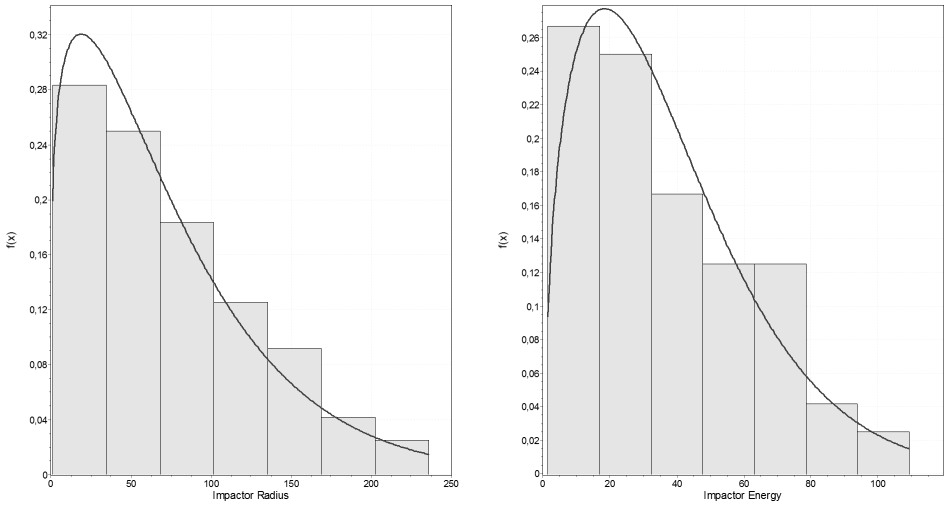


Figure 2.8: Reference damage data superimposed on impact threat map

The deductive problem approach was able to interpolate the impactor radii and energy for 110 out of the 120 data points as shown in Figure 2.8. The remaining data points fell out of bounds of the contour map for impactor sizes smaller than 1mm. At these values, MIDAS-M is at the limits of its capabilities to model a significantly small impactor (≤ 1mm radius). The SRM limits also distinguish the region of low- and high-consequence. The low-consequence region, which contains 89% of the 110 data points deduced, requires temporary repairs which are allowed for a specific time-frame. After the allotted time the defect must be repaired with a permanent solution. Conversely, the damage that fall outside of this region require the aircraft to be immediately grounded until the damage is corrected permanently. In this case study, 11% of calculable threats fell in the high-consequence region.

2.5.2. HISTOGRAMS OF IMPACT THREATS



(a) Weibull(3P) histogram of impactor radius (b) Weibull(3P) histogram of impactor energy

Figure 2.9: Weibull(3P) histograms of risk sources from MIDAS-M

To further understand the variation in impact threats, distribution curves of impactor radius and energy are analysed. For the sample set, four different distribution curves were tested following the steps taken in the works by Chen *et al.* [30]: the Weibull, log-logistic, lognormal, and normal distributions. Chi-squared test is applied to obtain the p-values exhibiting the goodness of fit of each distribution, as stated in Table 2.7.

There is a variation in the goodness of fit for both impactor radius and energy, but the normal distribution lags far behind. In regards to impactor radius, Weibull (3P) distribution has the strongest significance and is well correlated compared to the others. Conversely, impactor energy had weaker significance values for all four distribution, with log-logistic (3P) being the highest. However, with a 0.08 difference between Weibull and log-logistic, the former is chosen to characterise both impactor radius and energy.

By choosing the 3-parameter Weibull distribution for the sample set, the likelihood

of certain impactor radius and energy can be estimated. However, it is important to distinguish that these curves do not indicate typical combinations of impactor radius and energies. Hence, the two trends as shown here are completely independent. The Weibull parameters of the two distribution curves are summarised in Table 2.8.

Table 2.7: Chi-square test p-values, goodness of fit

	Impactor radius	**Impactor energy**
Weibull (3P)	0.76	0.42
Normal	0.34	0.12
Lognormal (3P)	0.35	0.32
Log-Logistic (3P)	0.38	0.55

Table 2.8: Weibull parameters of sample distribution curves

	Impactor radius	**Impactor energy**
Scale (η)	78.5	41.0
Shape (β)	1.21	1.42
Location (γ)	0.11	0.82
Mean	73.7mm	38.1J
Median	58.1mm	32.5J
Sample minimum	1mm	1.5J
Sample maximum	235.8mm	109.4J

2.5.3. RISK ANALYSIS OF IMPACTOR RESULTS

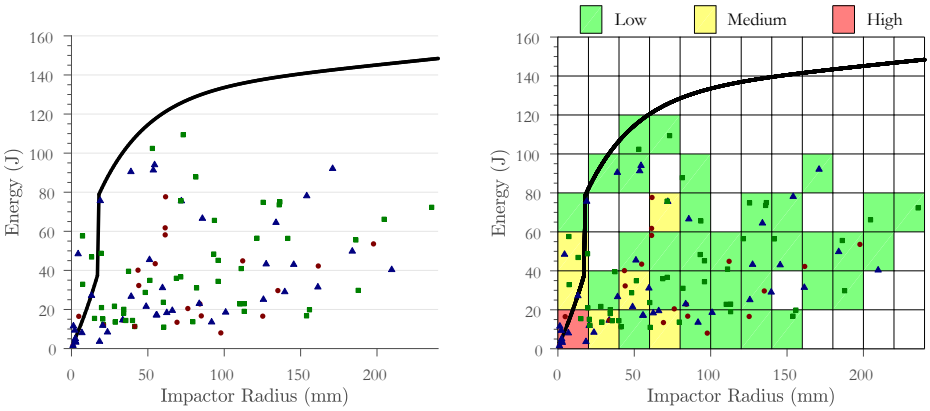
With the threats calculated from the damage dimension data, Figure 2.10a shows the general spread of the impactor radius and energy. The damage limits from SRM are converted in terms of impact threat (see Equation 2.5a and 2.5b). This dividing line in Figure 2.10a and 2.10b separates the distribution of impact threats into two regions with low-consequence below the curve and high-consequence above the curve.

$$E(R_i) = \begin{cases} 0.02826R_i^2 + 1.657R_i + 1.038 & \text{for } R_i < 17 \quad (2.5a) \\ 130.4e^{0.0005403R_i} - 92.41e^{-0.03111R_i} & \text{for } R_i \geq 17 \quad (2.5b) \end{cases}$$

Where,
E is energy
R_i is impactor radius

To associate risk to the predicted impactors, first cost is assigned to low-consequence and high-consequence impact threats. To quantify the consequence in terms of repair cost Table 2.6 will be used to get a weighted average of high- and low-consequence. About 11% of the threats are found to be of high-consequence, so by taking the expected cost of approximately top 10% in Table 2.6, the assumed cost of that region is

set to $962.54. The expected value of the remaining cost data is $217.13, which is the cost set for low-consequence.



(a) Impactor radius and energy

(b) Risk categories of impactor

Figure 2.10: Risk of impactor

Second, the likelihood of a certain threat needs to be quantified. Figure 2.10a is discretised into segments of 20mm x 20J. The specific size of the segment has been motivated by the sharp change in the threat limit curve at 17mm impactor radius. Each of these segments hold a share of low- ($\frac{n_{i,low}}{n_{i,total}}$) and high-consequence ($\frac{n_{i,high}}{n_{i,total}}$) threats. Using Equation 2.3 the segment likelihood is captured with respect to the total sample, and the risk value of each segment is calculated using the previously set costs ($962.54 and $217.13). The calculated risks are normalised using Equation 2.4 and by sorting the segments into their respective risk categories (Low $ROI_{i,norm} \leq 0.2$, Medium $0.2 < ROI_{i,norm} \leq 0.6$, High $0.6 < ROI_{i,norm} \leq 1$) the map in Figure 2.10b is produced.

The results show a significant clustering of data in the 0-20mm and 0-20J region leading the segment to be in the High-risk category. Using Equation 2.3 the risk of this segment is quantified as:

$$ROI_i = \left(\$962.54\frac{4}{11} + \$217.13\frac{7}{11}\right)\frac{11}{120} = \$44.75 \tag{2.6}$$

Since this segment has the highest ROI_i it is set as benchmark $ROI_{max} = \$44.75$ in Equation 2.4, i.e. $ROI_{i,norm} = 1$ for this example. Additionally, the segments at 0-20mm and 20-60J, and the segment of 20-40mm and 0-20J are assigned to Medium-risk also due to clustering. Conversely, many of the segments in the low-consequence region are denoted as Low-risk, due to the scattering of the threats. Nevertheless, there are some segments, which despite the low-consequence, result in Medium-risk due to the high clustering of the data points. Take the segment contained by 20-40mm and 0-20J again as an example. It contains 12 low-consequence and 0 high-consequence, by using Equation 2.3 the ROI_i of this segment is $21.71 and $ROI_{i,norm}$ is therefore $\frac{\$21.71}{\$44.75} = 0.49$. This behaviour of Medium-risks occurring below the threat limit is due to the cost not scaling

with the severity of the impact threat. The fixed nature of the cost means that risk values are more sensitive to clustering of threats rather than proximity to or ability to exceed the threat limits. Table 2.6 was used to assume the fixed values for C_{high} and C_{low} because the cost range can be broad. The precise cost values of each segment cannot be estimated, meaning that the severe ends of this cost range are not captured in the current calculations of ROI, potentially over- or under-estimating the risk in some cases.

2.6. DISCUSSION

In the setup of developing MIDAS-M and the case study using maintenance data, key assumptions are made. These assumptions and their effect on the results are discussed both from the perspective of the theoretical approach and engineering application of impactor risk.

Superimposing the bending and membrane deformation in MIDAS-M introduced a transition region. Through verification of MIDAS-M against the FEM model, the applicability is demonstrated to be linked to the thickness of the plates. The limitation of the plate thickness follows from the assumed interaction of bending and membrane deformation contributions occurring in this transition region. The difference in deformation shape for the 3-4 mm thick plates can be attributed to an overestimation of the bending contribution. The maximum force estimation errors can also be significant for thinner skins (<1.5mm) at high energies. Nevertheless, to address these errors and broaden the application of the model to a wider range of plate thicknesses, the definition of the assumed state of strain of the plate must be revisited.

The impactor risk analysis of the threats obtained from MIDAS-M is sensitive to a number of factors. First of all, the sizing of the risk grid can change the resolution of the analysis, consolidating the cluster of threats in a different manner. Next, the consequence of a threat was quantified with repair cost only, and acquired from a general survey. The cost can change depending on the aircraft operators. Furthermore, the cost is not the only form of consequence, so operators may choose to include indirect cost or make it multi-variate by combining other factors such as downtime. Lastly, the ranges assigned to a risk category (Low, Medium, High) will affect the designation of each segment. The results shown constitute one example of how the impact damage analysis of maintenance data can provide aircraft operators with a useful risk assessment. There are myriad ways to set up the analysis, but the process by which the risk analysis is conducted would remain the same.

2.7. CONCLUSION

The usual approach of determining the damage resulting from a certain impactor, characterised by material, size, and energy, has been reversed to test the degree to which damage dimensions can be used to deduce and identify the source of the damage. The deductive approach captures the variability in the impact threat characteristics (size and energy). This variation in impact threats causes MRO organisations to experience unplanned maintenance with a range of severity and cost. To demonstrate the utility of predicting impactors from a structural damage dataset, a risk-based approach is employed on the impactor results.

The impactors predicted by MIDAS-M have historically led to aircraft maintenance, and the same threats will pose a risk to operations in the future. The threats have a wide range of impact energy and size. The likelihood is based on the energy-size probability distribution, and the consequence is determined by the Structural Repair Manual (SRM) limit splitting the data into high- and low-consequence threats. Approximately 11% of the impact threats caused damage above the SRM limit, which has an average direct repair cost of four times that of a low-consequence impact. As a result, the range of impact threats of the highest risk was found to be 0-20mm by 0-20J. However, medium risk can also occur at impactor sizes as large as 80mm and for energies as high as 80J. A practical way that MRO organisations can use this information is to identify areas in the workshop, apron, runway, etc. that may contain potential impactors within these ranges and set up mitigation plans to reduce the probability of damage. Furthermore, the risk analysis conducted in this chapter is from the perspective of maintaining an aluminium aircraft. However, the consequences to these same threats would be different for composites. The difference in impact risk is explored in Chapter 3.

Several recommendations can be identified for both MIDAS-M and the risk-based approach. Beyond the way deformation theory is implemented, the range of impact scenarios for MIDAS-M can be extended. Currently, the model only considers flat plates with perpendicular impacts. However, fuselage sections can be single or double curved surfaces that have different responses to both perpendicular and angled impacts. Accounting for these factors may also lead to modelling of elliptical damage. Additionally, the development of MIDAS-M started with the assumption of quasi-static impact, but this may not apply to certain impactor size or energies. Furthermore, adding stringer and frame interactions could allow for more accurate modelling of off-centre impacts, covering a larger area of the aircraft. As for the risk-based approach, the consequences are set in a deterministic manner with fixed values for low-cost and high-cost. In practice, there are other factors to consider beyond direct repair costs such as cancellation of flight, delay, or availability of resources. For example, damage above the SRM limit is not necessarily a high-consequence event (i.e. cost due to disruptions) if the aircraft was scheduled for maintenance, during which the repairs can be conducted in parallel. Therefore, expanding the risk application in a non-deterministic manner may provide a more realistic depiction of operational risks.

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3

ASSESSING RISK OF IMPACTORS INDUCING DAMAGE ON COMPOSITES

This chapter builds on the previous chapter by modelling the response of a composite plate to the impact events deduced from metal plates. The model addresses a gap in the knowledge regarding the types of damage to be expected over the lifetime of a new generation of composite aircraft. Thereby, based on metal damage, a dataset of expected impact damage is obtained for composites, including surface dent damage, fibre breakage, or penetration. A risk assessment is conducted on the predicted impactors, incorporating maintenance cost as the primary indicator for event consequence. This assessment shows the risk the impactors pose on both the metal and comparable composite structure, and allows aircraft operators to anticipate and plan maintenance actions. Combining the inductive results with risk analysis determines the frequency and severity of damage on a future composite aircraft, thereby aiding in maintenance decision-making.

Parts of this chapter have been published in the International Journal of Impact Engineering [1]

3.1. INTRODUCTION

In order to counter the aforementioned data constraints for young composite aircraft, the inductive process takes advantage of the similarities between the generations aircraft. Using Boeing 777 and 787 as examples of the two generations of aircraft, the key similarities between them are: 1) both are designed for long-haul flights, experiencing a similar operational profile and 2) both aircraft have similar fuselage dimensions (barrel diameter Boeing 777 - 6.20m, 787 - 5.77m) [2]. While the frame and stringer pitches do differ, the assumption that they both will encounter similar types of impact threats with the same likelihood is still valid due to the similarity in fuselage size and operations. Since the metal aircraft have been flying for a longer period, there is a sufficient amount of damage data to analyse the different impactors that typically strike an aircraft.

Extending upon MIDAS-M summarised in Chapter 2, P. Massart [3] developed a composite counterpart called Modelling Impact Damage on Composite Aircraft Structures (MIDAS-C). MIDAS-C is used to simulate a range of impactors with different characteristics striking a composite plate (inductive problem). Estimates of the final damage dimensions induced by these impacts are collected to identify particular damage thresholds typically associated with composites (surface dent, Initiation of Fibre Breakage (IFB), Delamination Threshold Load (DTL), and penetration [4]).

A case study has been set up to predict future composite impact damage. A metal and a composite plate based on the CODAMEIN [2] properties are defined. The metal damage dimensions obtained from a Boeing 777 fleet dataset are used in conjunction with MIDAS-M and the defined metal plate, to deduce the impactors (source of risk). These same impactors are then input for MIDAS-C to induce the damage they would create on the composite plate. Thereby, rather than waiting for the composite damage dataset to grow over the aircraft's life-cycle, the inductive problem obtains the future damage dimensions and limits, from which the impactor limits can be inferred. Additionally, with the likelihood of particular impactor characteristics and the associated consequences known, a risk assessment is conducted to quantitatively compare the differences between the two materials in operations.

This chapter consists of six sections. First, the analytical approach of MIDAS-C and its functionality is discussed. Then the performance of MIDAS-C is tested against experimental drop-tests. Next, the case study set-up defines the plates being tested for both metal (MIDAS-M) and composite (MIDAS-C), along with the results of deductive problem providing the predicted impactor characteristics. These impactors are used as input for MIDAS-C resulting in contour maps showing feasible damage regions and a comparison of impactor risks for both materials. Based on the results the limitations of using the outlined approach for the specific case study are discussed. Finally, the conclusions on the use of MIDAS-C for predicting composite impact damage and risk analysis based on metal damage data are addressed, including future possibilities.

3.2. COMPOSITE IMPACT MODEL (MIDAS-C) SUMMARY

MIDAS-C has been developed to model impact damage on composite plates. Impact leads to stresses causing different types of failure. The types of damage experienced by composites caused by impact include forms of surface damage (cracks and indentations)

or subsurface damage (e.g. matrix cracks, delaminations and fibre breakage [4]). For details on the development process of MIDAS-C the reader is advised to refer to the thesis by P. Massart [3]. This section will summarise the approach employed in MIDAS-C to predict impact response, and how it is different from MIDAS-M.

Both MIDAS-M and -C address local and global modes of deformations, but the interaction and the resulting shape of these deformations differ. As outlined in Chapter 2 MIDAS-M implements an additional "transition" region between the local and global deformation modes. However, the MIDAS-C approach for modelling composite damage follows the assumed deformation proposed by Shivakumar *et al.* [5] and Abrate [6] which simply superimposes the local indentation following the shape of the impactor on the global deformation. The resulting shape of MIDAS-C is illustrated in Figure 3.1.

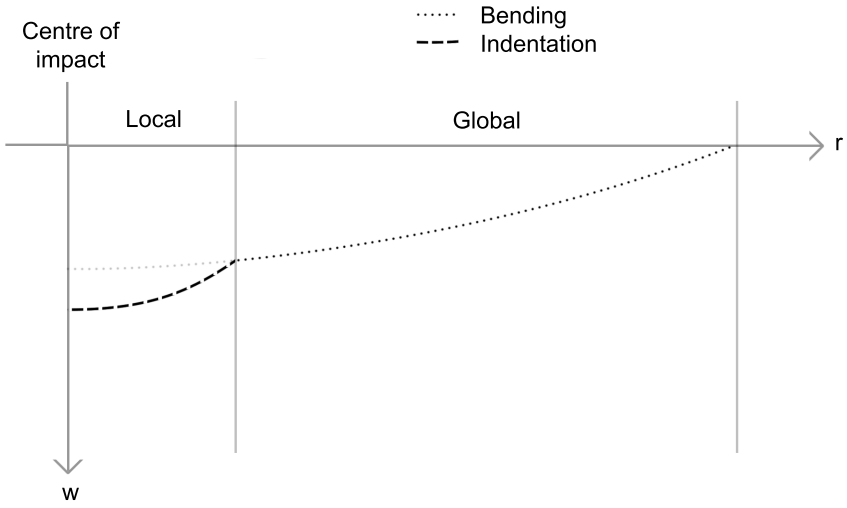


Figure 3.1: The event's plate deflection based on a superpositioning of the local and global deformations [3]

Despite the differences in the deformation shape, both forms of MIDAS (-C and -M) assume the same boundary-dependent quasi-static impact. The response of a composite plate to an impact is characterised in five stages (Figure 3.2): elastic response, delamination onset, delamination growth, fibre breakage, and penetration. Elastic response of the plate is in the form of small displacement bending [7, 8], with little to no visible surface damage. If the load continues to increase a delamination is triggered, indicated by a sudden load drop denoted as Damage Threshold Load (DTL) [9]. Further, the delamination continues to grow, requiring less load to increase the plate displacement due to the lowered bending stiffness [7, 10]. Then when a critical displacement and load is reached the fibres break at either the top or bottom of the plate. Fibre breakage is an indication of imminent complete failure and penetration [7, 10, 11]. While there is still load carrying capacity with broken fibres, a conservative approach would be to keep the threshold difference between fibre breakage and penetration small.

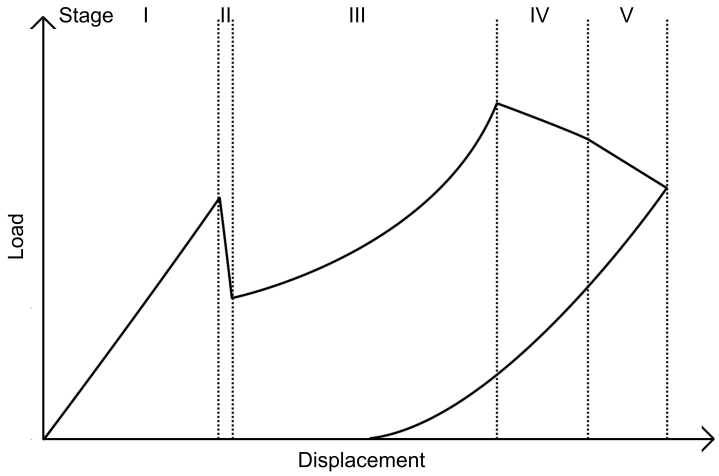


Figure 3.2: Simplified 5-stage response of composite response (based on Wagih *et al.* [7]) [3]

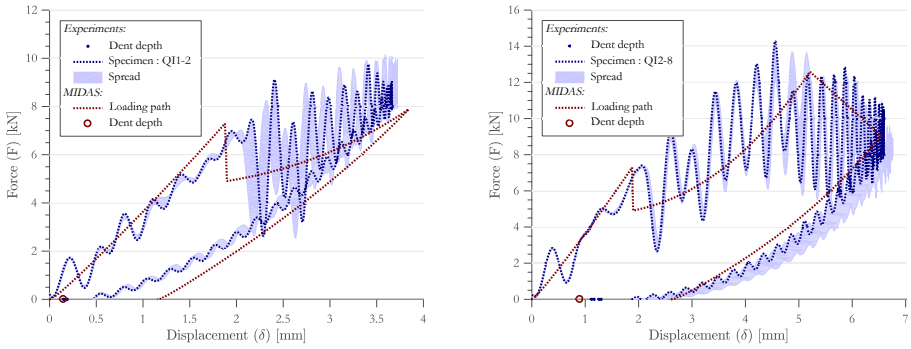
3.3. VALIDATION WITH DROP WEIGHT TESTS

The analytical model MIDAS-C has been validated through drop-test experiments on composite specimens. The experiment design follows the procedure as defined by ASTM standard D7136 [12], which is typically used to measure the damage resistance of a composite to an impact event. A quasi-isotropic (QI) layup using Hexcel AS4/8552 carbon epoxy (Table 3.1) has been impacted at four different impact energies, repeating each scenario four times. Some of the experiments will be presented in this section to compare the performance of MIDAS-C in simulating impact responses of actual impact events. For more detailed information on the setup of the drop-weight tests and additional experiments, the readers are advised to refer to the master thesis of P. Massart [3].

Table 3.1: Material properties of Hexcel AS4/8552 carbon epoxy [3]

UD Ply Properties					**UD Ply Strength**				
E_{11}	E_{22}	G_{12}	ν_{12}	t	X_t	Y_c	Y_t	Y_c	S_{12}
GPa	GPa	GPa	-	mm	MPa	MPa	MPa	MPa	MPa
131	9.2	4.8	0.3	0.1825	2068	1531	64	268	92

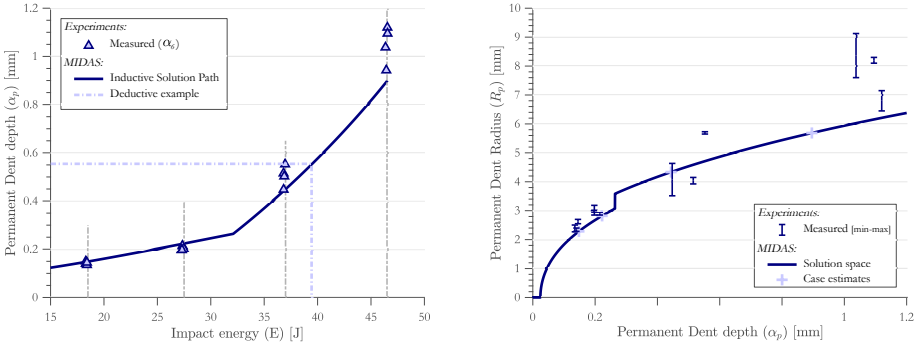
Inductive validation takes the known parameters of the experiment to recreate the damage dimensions using MIDAS-C. The comparison presented in this section addresses the validity of the force displacement plots of MIDAS-C. The analytical model should be able to the identify the different stages of impact response as discussed in Section 3.2. The recorded impact response for the highest and lowest impact energy cases (i.e 18.4 J and 46.5J) and the corresponding prediction from MIDAS are shown in Figure 3.3. When evaluating the performance of MIDAS-C it should be noted that the experiment manual measurements inherently have significant scatter.



(a) Impact energy of 18J (b) Impact energy of 46J

Figure 3.3: Comparison of MIDAS-C with quasi-isotropic (QI) layup type [3]

The impact response comparison for 46J energy depicts that the different stages (elastic response till DTL, delamination growth, IFB till unloading) are indeed present in the experimental data. Two aspects that MIDAS-C is in good agreement with the experimental results are, 1) the transition between the individual phases, and 2) the predicted initial elastic response. However, to check whether the final residual dents are predicted accurately requires a knee-point diagram (Figure 3.4a) for dent depth, and dent depth-radius plot (Figure 3.4b). The Initiation of Fibre Breakage (IFB) is the knee-point where the slope of the dent depth trend changes. In regards to the predictions of the dent depths, the pre-IFB depths are more accurate than post-IFB. Similar accuracy is found for the dent depth-radius plot at pre- and post-IFB load. Although, the larger deviations can be attributed to measurement scatter of the experiment, the general trend of both residual dent dimensions (depth and radius) are captured well.



(a) Permanent indentation as function of energy (b) Dent radius as function of dent depth

Figure 3.4: Comparison of dent estimates with relaxed dent of quasi-isotropic (QI) layup type [3]

3.4. CASE STUDY SET-UP

MIDAS-C has been developed to take input of expected impactors to predict future damage on composite plates. A case study is designed to compare the performance of the composite plate versus its metal counterpart. The comparison is made possible by using MIDAS-M to obtain the predicted threats as inputs based on the recorded damage dimensions of B777 fuselage from a fleet of a major European carrier.

3.4.1. DEFINING THE COMPOSITE AND METAL PLATE

Table 3.2: Material properties of Al2524 [13, 14]

Yield stress	**Ultimate stress**	**Fracture strain**
MPa	MPa	%
275.8	413.7	21

Table 3.3: Range of wide-body aircraft fuselage dimensions [2]

Aircraft type	**Stringer pitch**	**Frame pitch**	**Skin thickness**
	mm	mm	mm
B777	230	530	1.0-2.6
B787	227	610	–

Table 3.4: Plate properties of target plates used in case study

Type	**a**	**b**	**t**	**Ex**	**Ey**	**D**
	mm	mm	mm	GPa	GPa	Nm
Metal	230	530	2.52	70	70	102.6
Composite	227	610	2.9	54.1	54.1	121.6

The case study is intended to demonstrate the process of using damage found on Boeing 777 to predict impact damage on Boeing 787. The target plates have to represent respective aircraft's fuselage structures. Hence, they are based on the work of Haase and Mikulik [2] (CODAMEIN), in which fuselage dimensions of both Boeing 777 and 787 are summarised, and a representative (composite) aircraft structure is defined. The layup sequence for this fuselage section is $[(0/90)/0/45/90-45/0/45/90/-45]_s$. The top layer (indicated by (0/90)) is a fabric ply with a thickness of 0.25 mm, while the remaining layers are unidirectional plies with thicknesses of 0.15 mm. The material properties of the actual composite aircraft (Boeing 787) are not specified by Haase and Mikulik, and are confidential in all relevant SRM chapters. The range of fuselage dimensions and relevant material properties of aluminium Al2524, on the other hand, are summarised in Table 3.2 and 3.3. The resulting target plates are summarised in Table 3.4. The fuselage dimensions (stringer and frame pitch) defined the plate size.

3.4.2. MAINTENANCE DATA AND DEDUCED IMPACTORS

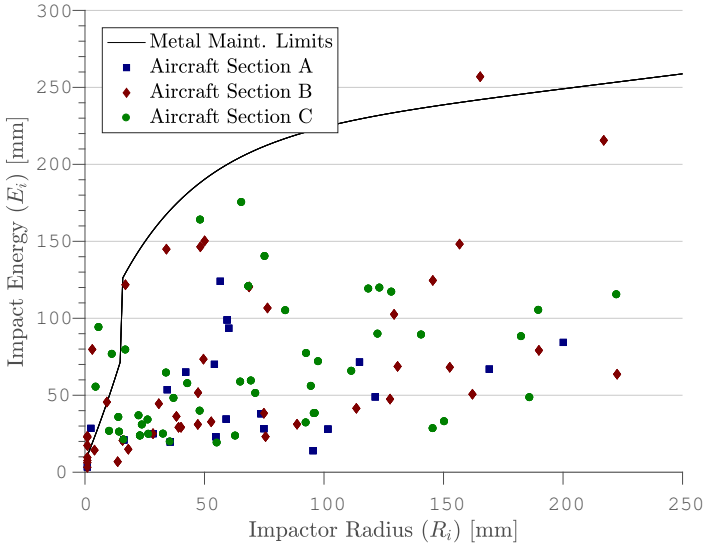


Figure 3.5: Predicted impactor radius and impact energy from MIDAS-M, input for MIDAS-C

The same damage dimension dataset from the development and application of MIDAS-M (Subsection 2.4.1) is used along with the newly defined metal plate (Table 3.4) to predict the impactors for MIDAS-C input. Following the analytical model procedure of MIDAS-M and the defined metal plate in Table 3.4, the impactor threats are predicted and presented in Figure 3.5. The figure also contains the maintenance limit (obtained from the SRM) separating the impactors that would require permanent repair (above the limit), or temporary repair (below the limit). Note that 13 of the predictions exceed the permanent repair limit. Although the other predictions require time-limited temporary repairs at minimum, operators may choose to skip the temporary repair step and immediately opt for a permanent solution [15]. Upon inputting the predicted impactor radius and energy in MIDAS-C, the same scatter plot will be expected (shown in Section 3.5) but with different limits specific to the composite plate: no dent, initial fibre breakage, penetration.

3.4.3. RISK ASSESSMENT OF IMPACTORS FOR COMPOSITE PLATE

RISK ASSESSMENT FRAMEWORK

To mitigate the potential impact to an aircraft, MRO organisations and operators can quantify the risk using a 5-step Safety Risk Management Process setup by International Civil Aviation Organisation (ICAO) [16]: hazard identification, hazard probability, hazard consequence, risk assessment, risk control/mitigation. The process has been modified for this case study as shown in Figure 3.6, because deducing the impactors for composite

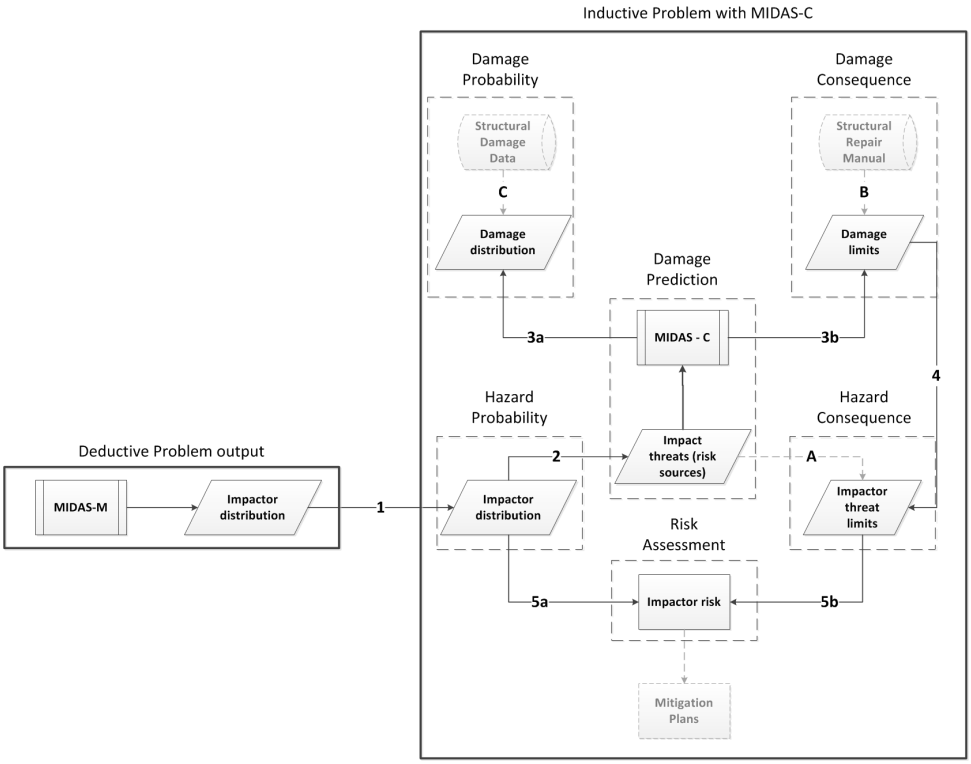


Figure 3.6: Process representation of the proposed approach towards composite impact risk assessment, based on ICAO framework [16]

fuselage is hindered by the smaller damage dataset (Constraint B) and the SRM provided by OAM does not give complete design properties of the structure and thereby its failure limits (Constraint C). As a result, performing impactor risk assessment directly is constrained due to the lack of material properties and failure thresholds (Constraint A).

Hence, instead of waiting on the composite aircraft to operate over a long period of time, the deductive problem of MIDAS-M uses the dent damage dimensions (length, width, depth) of an equivalent metal aircraft to deduce the impactor characteristics (energy and size). It is assumed that these same impactors will strike a composite aircraft with the same likelihood (Step 1), and MIDAS-C uses them as input to induce damage on a comparable composite skin (Step 2). Thereby, a dataset of future damage dimensions (Step 3a) and limits (Step 3b) are obtained, from which the impactor limits can be inferred (Step 4). Finally, MIDAS-C, using the predicted impactors from MIDAS-M, generates impactor probability (Step 5a). The probability is combined with impactor consequences (Step 5b) to conduct impactor risk assessment.

DETERMINING IMPACTOR RISK

For the metal case the maintenance limit curve divides all possible events into two consequence regions: low-consequence (below the curve), and high-consequence (above

the curve). Any low-consequence threat requires temporary repairs, but a threat that is high-consequence requires an immediate permanent repair solution. Following the surveyed cost report on "The economic cost of FOD to airlines" and the distribution of high- and low-consequence threats occurrence, to keep the analysis dimensionless a cost ratio of 4:1 is applied [15, 17]. Indirect cost is not accounted for due to its dependency on when the damage occurred rather than the damage severity itself (See Chapter 4 [15]).

With the consequence quantified, the second element to quantify is the likelihood, and thereby obtain risk of impact (ROI) . The global space of impact threats found in Figure 3.5 is once again discretised into a grid of segments following Subsection 2.4.2, sized to be 20mm by 20J. The likelihood of a segment is then the ratio between number of threats in a segment ($n_{i,total}$)and total number of threats (n_{total}). As a result of the way the consequence and likelihood of a threat are defined, the general equation for the risk of each segment follows Equation 2.3.

Applying Equation 2.3 to the impactors obtained from MIDAS-M and presented in Figure 3.5, results in a categorised risk map of all threats in Figure 3.9a. The maximum risk value (ROI_{max}) obtained by a segment in the global space is 0.15. Previously in Subsection 2.4.2, the risk categories for metal are presented as normalised risk ranges: Low ($ROI_{i,norm} \leq 0.2$), Medium ($0.2 < ROI_{i,norm} \leq 0.6$), High ($0.6 < ROI_{i,norm} \leq 1$). However, in this case study the metal maximum risk value 0.15 is used as a benchmark, to reformulate the three risk categories as: Low ($ROI_i \leq 0.03$), Medium ($0.03 < ROI_i \leq 0.09$), High ($0.09 < ROI_i$). This is to ensure that the comparison between metal and composite remains consistent and captures the change in actual risk from metal to composite.

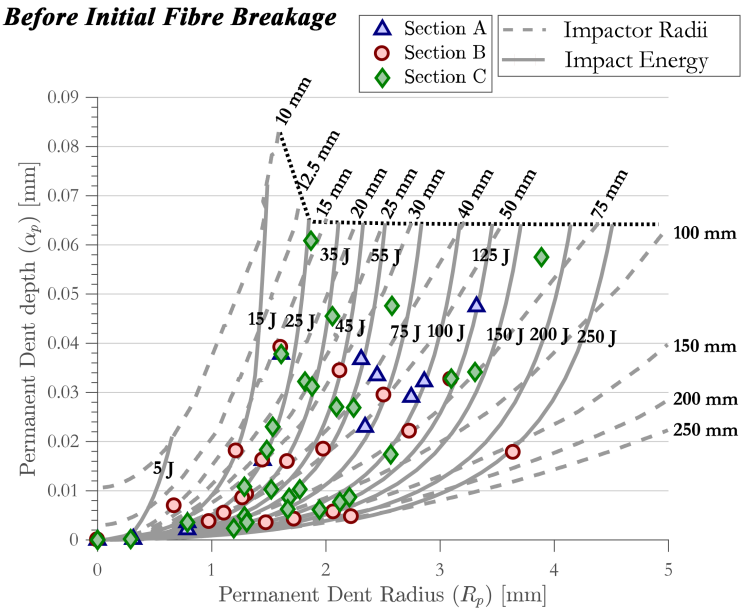
By performing risk assessment on MIDAS-C, results in a similar categorised risk map for a composite plate (see Figure 3.9b in Subsection 3.5.2). The penetration limits will be used to define the separation of high- and low-consequence impact, because in practice irrespective of plate dimensions all holes require permanent repairs. To allow for a comparison of metal and composite categorised risk map, the risk categories (Low ($ROI_i \leq 0.03$), Medium ($0.03 < ROI_i \leq 0.09$), High ($0.09 < ROI_i$)) will remain the same.

3.5. RESULTS AND ANALYSIS

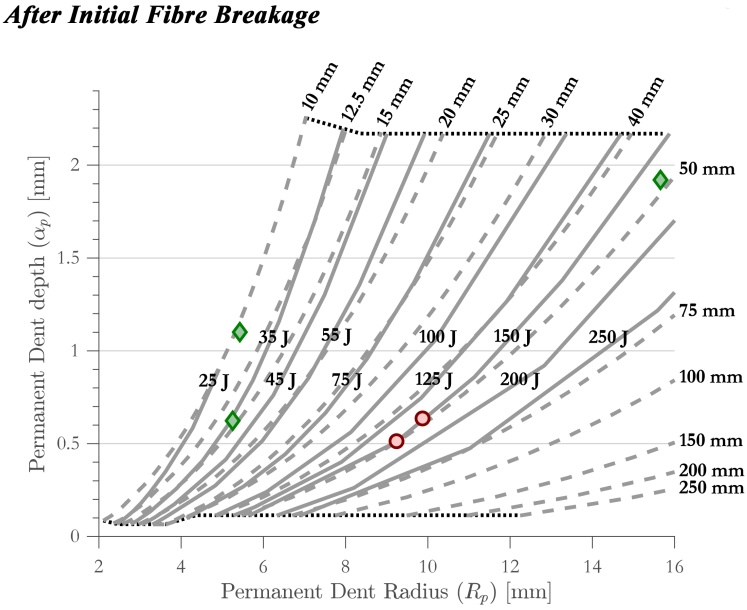
Using MIDAS-C, a contour map of all possible damage dimensions is generated for the composite plate. The individual impactor characteristics obtained from MIDAS-M are included in the contour to show the composite damage they would create. The results are also conducted for the same three fuselage sections (A, B, and C) as in Section 2.5. The boundaries of the contour map define the limits for IFB and penetration, thereby allowing for impactor limits to be determined and applied for risk assessment. Finally, for both metal and composite threat risk maps are presented and compared against each other using the limits of Low ($ROI \leq 0.03$), Medium ($0.03 < ROI \leq 0.09$), and High ($0.09 < ROI$).

3.5.1. GENERAL CONTOUR MAP AND FINAL DAMAGE DIMENSIONS

Of the initial 120 impact damage dimensions, MIDAS-M was able to successfully determine 110 impactor threats as shown in Figure 3.5. Using these impactors as inductive problem input for composite, impact event contours are obtained from MIDAS-C.



(a) Damage contour map before IFB



(b) Damage contour map after IFB

Figure 3.7: Damage contour map of MIDAS-C with predicted threats from MIDAS-M [3]

The resulting contour map Figure 3.7 consists of two parts in line with the initial fibre breakage limit. The contour maps show that the majority of the threats result in a dent below the IFB limit, whereas only four cases are shown within the advanced fibre breakages stage. However, 20 entries are not included in the contour map illustration. These threats are expected to cause complete penetration. The conversion process is summarised in Table 3.5.

Table 3.5: Summary of Composite sample data set conversion

			Composite		
Section	**Sample Size**	**No Dent**	**Residual Dent**	**IFB Dent**	**Penetrations**
A	23	7	12	0	2
B	47	9	20	2	12
C	50	12	29	2	6

3.5.2. MAINTENANCE RISK OF IMPACT THREATS FROM METAL VS. COMPOSITE

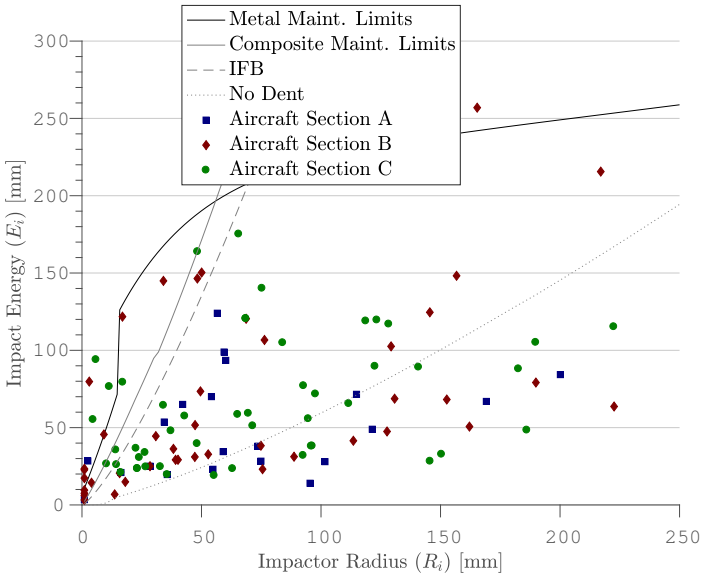
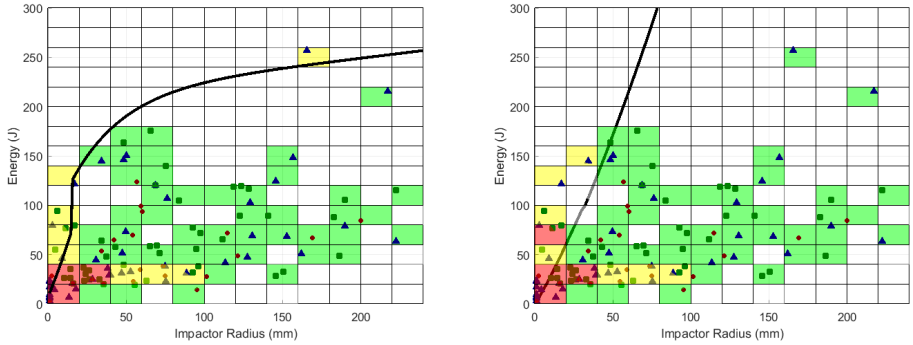


Figure 3.8: Impact threat in terms of impactor radius and impact energy with respect to both metal and composite maintenance limits

From the inductive process of MIDAS-C the damage limits of no dent, IFB, and penetration are directly quantified into impactor limits. These limits are overlaid on Figure 3.5, providing a direct comparison of how damage limits change between composite and metal plate in Figure 3.8. Thereby the separation of high- and low-consequence regions are also changed. Taking penetration limit as the border between the two con-

sequence regions for composite, the risk maps of composite and metal are compared in Figure 3.9.

There are three segments that have changed in risk categories from metal to composite. For impactor radius of 0-20mm at energies 60-80J, and 20-40mm at 140-160J, the risk category has gone from Medium to High, and Low to Medium respectively. The one other change is in the opposite direction going from Medium to Low for impactor radius of 160-180mm at 240-260J. These changes have occurred due to the high sensitivity of the risk values to consequence (i.e. cost).



(a) Metal categorised impact risk

(b) Composite categorised impact risk

Figure 3.9: Impact threats risk comparison between metal and composite plate

These figures indicate that metal and composite have similar risk performance for large majority of the threats. Particularly for impactors larger than 60mm at energies lower than 200J, covering nearly 45% of the sample data, there is no difference in risk between composite and metal assuming the consequences in terms of cost are the same. Generally speaking the risk assessment exercise with penetration limits indicates that the larger and high energy impact poses less risk to composite than metal. However, it should be noted, that the extent of internal damage for the composite plate is not indicated by MIDAS-C. Conversely, the composite is found to be more sensitive to smaller impactors (0-20mm) than in the case of a metal plate.

3.6. DISCUSSION

Key assumptions were made in order to develop MIDAS-C and apply it to a case study. These assumptions ranged from the limits of the theoretical impact model to the implications of risk assessment for maintenance operations.

Upon examining the results of the obtained threats for risk assessment, a large portion of impactors were found to be smaller than 10mm in radius. In the development of MIDAS for both material types a quasi-static and boundary independent event is assumed, without the knowledge of the types of impactor to be expected. However, Olsson [18] indicates that impactor with small mass is considered to be a plate boundary dependent dynamic event. Therefore, the application of MIDAS-M to obtain impactor characteristics may not be suitable for a subset of the original damage dimensions used.

The impactors predicted from this subset thereby may not be relevant or accurate for the purposes of the case study. Yet at the other extreme of the impactor size, there are impactors predicted that are larger than the plate dimensions. In the implementation local and global behaviour point loads are considered, but due to the large impactor radii the validity of point load needs to be re-evaluated. Currently the results state that composites are not as prone to high risk from larger impactors. However, in reality these larger impactors will cause damage to the sub-structure and Barely Visible Impact Damage (BVID). Hence, the inclusion of sub-structure influences in MIDAS-C should be considered, along with the detectibility of the damage in within this region ($\geq 100mm$ radius). The model, in its present form, serves as a good starting point in quantifying and anticipating damage in composite aircraft structures but will need refinement to better account for inter-laminar damage (delaminations and their effects).

The setup of the risk assessment method imposes some limitations in its application. Risk analysis requires defining the consequence and likelihood, but due to the cost ratio of 4:1 (high- and low-consequence respectively) the risk values are highly sensitive to consequence. Furthermore, this cost ratio for direct repair cost is assumed to be the same for both metal and composite for ease of comparison purely based on the material difference. However, in practice the cost may not be the same, influenced by differences in the repair techniques and raw material. For more realistic quantification of the differences between metal and composite risk, exact cost ratios are required. Finally, the risk assessment is discretised into fixed segments, the sizing of which directly affects the risk values of those segments. Nevertheless, this case study is an example of the way in which impactor risk assessment can be carried out. In the end, the grid sizing is under the discretion of the end-user but the same procedure for risk-based analysis is applicable.

3.7. CONCLUSION

Motivated by the minimal amount of impact damage data for the new generation of composite aircraft, an analytical model Modelling Impact Damage on Composite Aircraft Structures (MIDAS-C) has been developed to simulate impact on a composite plate and predict the resulting damage. This process of inducing damage on a plate with an impactor of known size and energy is referred to as the inductive problem. The challenge however, is that the impactors that would typically strike a composite aircraft are not always known. Therefore, this study exploits the operational and dimensional similarities between the former generation metal aircraft and new generation composite aircraft. A previously developed model Modelling Impact Damage on Metal Aircraft Structures (MIDAS-M) uses known damage dimension data from a metal aircraft to deduce the impactor characteristics (deductive problem). These predicted impactors enable the inductive approach of MIDAS-C, as these impactors are used to predict the damage a composite aircraft would experience.

The analytical approach, MIDAS-C, combines local deformations and global deflections to capture the final damage type and dimensions after an impact event. The model identifies the different damage thresholds of the composite plate: surface dent, Initiation of Fibre Breakage (IFB), Delamination Threshold Load (DTL), and penetration. The performance of MIDAS-C has been validated against experimental results from drop-

weight tests. The inductive impact response of MIDAS-C was shown to be in good agreement for a quasi-isotropic laminate, accurately modelling the residual dent depth. However, as expected there was a larger variation in the predictions of permanent dent radius due to the scatter in manual measurements of the laminates. The deductive problem of MIDAS-M provided 110 unique impactors that were the input for MIDAS-C. These predicted impactors led to the following response on the composite plate: 25% no dent, 54% residual dent, 4% IFB dent, 18% penetration. Each of these types of damage would entail different repair types dictated in the SRM. The majority of the impactors led to some form of damage, the largest portion of which being residual dents that may contain internal failures such as delamination. The case study shows that for a given structure MIDAS-C can confidently estimate the different damage thresholds of the structure, as well as model individual impact events to predict the damage type and dimensions.

A proposed example of engineering application demonstrated in this study is a risk assessment of the predicted impact events. The predicted impactors assessed with respect to the likelihood and consequence in terms of direct repair cost, show differences between the two materials. From metal to composite three segments of the impactor characteristics changed risk categories. The two segments that increased in risk category for composite are for impactor radius of 0-20mm at energy of 60-80J (Medium to High), and 20-40mm at 140-160J (Low to Medium). The segment that decreased in risk category is for impactor radius of 160-180mm at 240-260J (Medium to Low). Considering that penetration limits of composites are chosen as the limits for high- and low-consequence, while metal limits are based on the Structural Repair Manual, there are no changes in risk for a large majority of impactors (radius ≥60mm at energy ≤180J). However, the difference in risk between the materials becomes larger if another damage threshold is chosen as the consequence limit for composite.

There are several avenues to further expand upon MIDAS-C development in the future. MIDAS-C simplifies the impact events it models, constraining the range of validity in an engineering setting. Although the spherical nature of the impactor is a good generic first step, in reality impactors can be deformable with different shapes. Hence, exploring other shapes and rigidity of impactors would allow for a wider application. Many of the predicted impactors are smaller than 10mm, for which a quasi-static and boundary dependent assumption may not hold. Furthermore, the boundary conditions do not account for the free movement of aircraft stringers and frames, especially for off-centre impact; MIDAS-C is restricted to central impact. Future improvements for MIDAS-C can be summarised to model: non-spherical and non-rigid impactors, curved target structures including stringer and frame interaction, small mass boundary independent events, and non-perpendicular and off-centre impact. As for the engineering application, apart from the assumptions of MIDAS-C and MIDAS-M, the risk assessment considers some assertions that could be made more precise. For instance, high- and low-consequence in terms of direct repair cost has been fixed as a 4:1 ratio for both metal and composite. However, this ratio is a generic approximation of temporary and permanent repair cost in aviation as a whole. Therefore, a more precise ratio for metal and composite respectively would provide more insightful differences in maintenance for impact damage related to the two materials. Additionally, the consequence limit, although defined by safety authorities and aircraft manufacturers, can still be under the

discretion of the MRO for composites. MRO organisations may be more conservative and consider any surface damage as "high-consequence" because the internal damage is not obvious. In such a case, a larger share of impactors would fall under the high-risk category.

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4

MULTI-CRITERIA REPAIR DECISION-MAKING MODEL FOR COMPOSITE STRUCTURES

Multi-criteria decision making (MCDM) model is developed aided by historical damage data. The proposed MCDM model focuses on decision alternative identification and evaluation for operational maintenance processes with short time horizons. Thereby, problems that need solutions in hours or a few days at maximum are resolved. This addresses a gap in literature, where MCDM methods are predominantly proposed for strategic maintenance decision making. The proposed approach addresses two distinct steps for 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 the qualitative and discrete operational factors that determine the available and feasible decision alternatives in the 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 existing maintenance and operational data. A decision tool has been developed and verified, showing the capability of the approach to systematically identify and evaluate operational repair decision making problems in a few minutes.

Parts of this chapter have been published in the Journal of Air Transport Management **68**, 152 (2018) [1].

4.1. INTRODUCTION

MRO organisations face difficult decisions on a daily basis, having to judge the appropriate course of repair action in the event of damage [2]. Maintenance decision-making is frequently complicated by scheduling constraints and resource availability. These limitations dictate the number of feasible maintenance options while adding to the complexity of identifying and selecting an optimal repair solution [3]. An additional problem is that maintenance events are often intermittent in practice [4], sometimes occurring years apart for a component. As a result, maintenance operators lack aggregated historical data and experience to systematically approach maintenance event resolution. This can and does lead to informal decision-making processes, with poorly defined criteria, and lack of a systematic approach to choose among competing alternatives for event resolution [5].

As a consequence, sub-optimal decisions may result [6], potentially leading to significant losses in money and time. Though estimates of effect on cost are sparse, several authors have indicated that 15-30% of total process time is wasted on retrieving the correct supporting information for maintenance decision-making [7, 8]. In terms of cost, making an incorrect decision has significant implications for repair and delay cost [9, 10]. To prevent these losses, a formalised approach for maintenance decision-making has to be in place.

Multi-Criteria Decision-Making (MCDM) process can be boiled down to three critical attributes as defined by Triantaphyllou [11, 12].

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 attribute, existing literature frequently assumes decision alternatives to be available at the beginning of the decision-making process. These alternatives are usually not known for maintenance processes at the operational level [5, 11, 12]. Hence, Boolean Decision Tree (BDT) is chosen from numerous methodologies to identify the 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. To do so Weighted Sum Method (WSM) is used to quantitatively analyse the alternatives against an established criteria of cost, survivability, and downtime. Consequently the contribution of this work is application-oriented, emphasising the integration of existing methods to fill gaps in 1) maintenance decision-making at an operational level, covering 2) option identification and 3) structured comparison and evaluation of decision alternatives.

This chapter is structured in four main sections. First, the methodology section details the selected MCDM models based on application and functional requirements. The proposed Multi-Criteria Decision-Making model consists of two modules: BDT and WSM. Subsequently, the results section demonstrates how the model has been implemented through an application for actual damage on a Boeing 777 outboard flap. The case study is a representative example of an operational decision-making process in

aircraft maintenance, and provides sensitivity analysis with respect to decision criteria weights. The proposed method is validated against the actual decision-making process, highlighting the advantage of using BDT and WSM. Finally, conclusions based on the findings of the research are presented, along with recommendations for future expansion.

4.2. MAINTENANCE MCDM APPROACH AT OPERATIONAL LEVEL

Numerous methodologies have been proposed in literature, including applications in the maintenance domain, for example the Weighted Sum Method (WSM), Analytical Hierarchy Process (AHP), Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE), Elimination and Choice Expressing Reality (ELECTRE), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Boolean Decision Tree (BDT), and Compromise Programming (CP) [13–55]. This section motivates selecting BDT for identifying feasible repair options and WSM for subsequently evaluating the alternatives.

4.2.1. OPTION IDENTIFICATION

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

OPTION IDENTIFICATION APPROACH

Identification of the maintenance options is based on the event attributes at the time of the repair. These include technical attributes of the repair process, as well as influencing operational factors such as logistics and asset utilisation, both of which 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 and requirements for identification, the 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 [26, 35], and supporting qualitative, multi-dimensional and discrete inputs [13]. If the number of attributes or attribute ranges considered are large, then the amount of available options to generate and evaluate rises rapidly, consequently increasing required computation time.

DETERMINING FEASIBLE OPTIONS

Before any decision is made, the current damage and operational situation has to be fully understood. Ideally a maintainer would like a wide range of repair options from which they can choose. However, due the severity of the damage or other operational constraints, it may be that some repair options are infeasible [56]. Therefore, the BDT prunes through all options to identify the repair options that are feasible.

The pruning process works as follows. Initially, all repair options are assumed to be feasible. With each consultation of the BDT factors, the repair option list either stays the same or some of the possibilities are eliminated. This consultation process continues

until the final factor is reviewed, and the maintenance scenario for the damage is defined with a set of possible repair options. A practical example of a pruning is given in Subsection 4.3.2.

4.2.2. OPTION EVALUATION

Having identified the feasible options, they can be compared to each other based on the decision criteria. As such, this section focuses on determining relevant evaluation criteria and an associated method, and outlining how this method can be applied in maintenance MCDM at an operational level.

DETERMINING EVALUATION CRITERIA AND METHOD

Within the maintenance domain, the MCDM criteria are highly application-dependent. Within the scope of this application, the criteria for which the feasible maintenance options are being analysed 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.

These criteria are motivated by their importance within the aircraft maintenance domain [56]. Operational maintenance processes in other industries may require different criteria for consideration.

The three criteria are quantitative, multi-dimensional, and continuous in nature. Functional differences among MCDM methods can assist in determining the most suitable evaluation method. For instance, CP requires an ideal solution to evaluate the "closeness" of the alternatives to this ideal [32, 33, 43, 57]. However, in practice there is usually never an ideal repair option because 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 [37, 42, 58, 59]. The pairwise comparisons work well in fixing a particular weight, especially when there is a list of sub-criteria. However, when using a limited number of decision criteria, the benefit of AHP over WSM quickly diminishes.

When considering the methods covered the field of MCDM, two methods are particularly suitable to identify the best maintenance option in this case: 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 utilised, providing similar outputs in terms of option ranking. However, TOPSIS introduces bias towards options that are 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 their discretion to make a judgement. Therefore, the WSM method is selected for the proposed approach towards decision-making for operational maintenance processes, because it can be easily implemented and adopted by practitioners.

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 each criterion 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 customisable by the decision-maker or in this case 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 4.1 shows how the final aggregate score ($R_{a,\text{agg}}$) for a maintenance option is calculated [28, 52, 53]. Equation 4.1 however requires determination of the individual criterion ratings, R_a.

$$R_{a,\text{agg}} = R_{a,\text{survivability}} \times W_{\text{survivability}} + R_{a,\text{cost}} \times W_{\text{cost}} + R_{a,\text{downtime}} \times W_{\text{downtime}} \tag{4.1}$$

Where,
$W_{\text{criterion}}$ is weight of a criterion, $0 \leq W_{\text{criterion}} \leq 1, \sum W_{\text{criterion}} = 1$

CRITERION RATING AND OVERALL EVALUATION

In order to rate each option based on the criteria weights, first the options are evaluated separately for each individual criterion. For any given maintenance event there may be a varied set of repair options. To differentiate the options from one another for each criterion, an individual criterion rating system is adopted. The individual rating system indicates 1 for the best option of the set, and 0 for 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 0 and 1 with respect to the best and worst option. Two different equations are used to calculate the criterion rating in a non-dimensionalised manner [56]. Equation 4.2 is used to calculate the rating for a criterion that should be maximised. Conversely, Equation 4.3 is used for a criterion that is to be minimised.

$$R_{a,\text{factor}} = \frac{x_a - X_{\text{min}}}{X_{\text{max}} - X_{\text{min}}} \tag{4.2}$$

$$R_{a,\text{factor}} = \frac{X_{\text{max}} - x_a}{X_{\text{max}} - X_{\text{min}}} \tag{4.3}$$

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

An aggregated weighted rating is finally obtained by inputting the criteria ratings into Equation 4.1. The option with the highest aggregate score is identified to the maintainer, and chosen as being the best decision for a given set of weights.

4.3. RESULTS

The proposed approach for option identification and selection is applied towards a practical case, which addresses an actual damage on a Boeing 777 outboard flap. In this particular case, after the damage occurred, the maintenance company decided upon a repair option through multiple days of discussion. The proposed approach was conducted, identifying and evaluating the repair options, leading up to selection of the most appropriate course of action.

The implementation of the methodology described previously, in the context of the case study is discussed first. Subsequently, results are presented with respect to option identification and evaluation. A systematic sensitivity study conducts a global search of weights 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, highlighting the several benefits of the proposed approach for maintenance MCDM at operational level.

4.3.1. IMPLEMENTATION

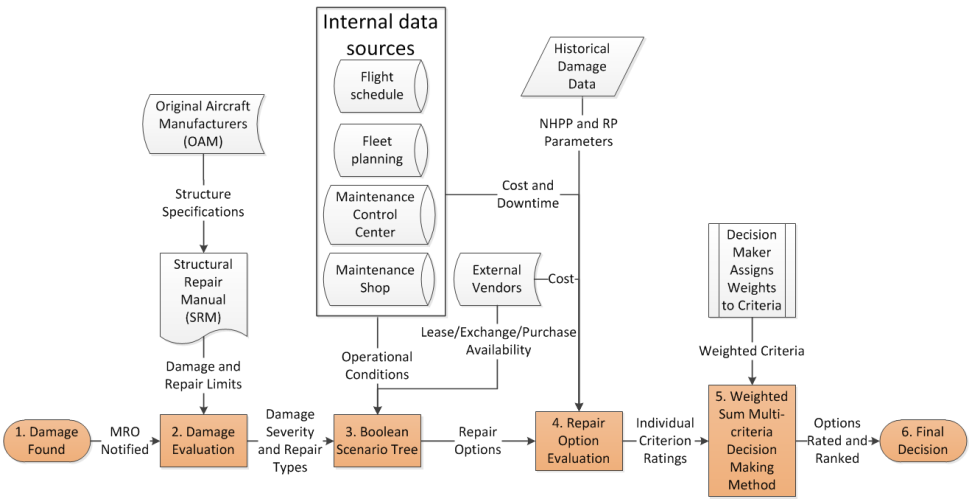


Figure 4.1: Case study implementation of maintenance MCDM model at operational level

Figure 4.1 presents how the approach proposed in Section 4.2 has been implemented for the Boeing 777 outboard flap case study. The core steps are comprised of 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 related to BDT factors and WSM weight settings. In total, the tool takes 5 seconds to run, provided all input information is available. In principal, any widely accepted program-

ming language can be used, including JavaScript as shown in Chapter 5 for developing an open-source version of the tool.

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 MRO organisation is notified to rectify the issue.

2. **Damage Evaluation**: as a second step, the MRO organisation evaluates the damage. This involves dispatch of technicians with knowledge of the structure 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 repairs, involving task instructions, damage limits, and the time-frame 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 BDT approach is used to formalise the identification of repair options. Subsequently, the tree can be pruned (see Subsection 4.3.2 for an example), yielding an overview of all feasible repair options, including scheduled time of individual tasks as output. Inputs are related to damage evaluation (i.e., technical characteristics of the event) as well as operational conditions and logistical constraints. With respect to operational conditions, internal data sources (including airline flight schedule, fleet planning, Maintenance Control Centre, and maintenance shop) are consulted to collect information related to current and future operational conditions. With respect to logistical constraints, the availability of lease, exchange or new parts is checked with external vendors, as MRO organisations typically have limited manufacturing capability.

4. **Repair Option Criteria Rating**: each option is rated against the decision criteria, which as mentioned are survivability, cost, and downtime. The rating of each criterion has been calculated in the following manner:

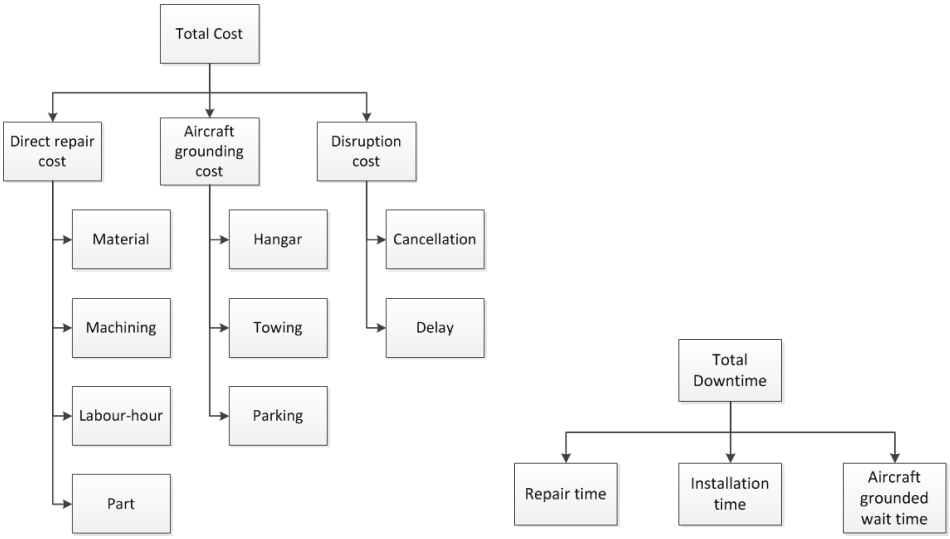
   (a) **Survivability**: repair options can involve temporary repair, a minimal repair action that is modelled through a power law Non- Homogeneous Poisson Process (NHPP) to estimate survivability over time. Options with follow-up actions that restore the part to an as-good-as-new state (either through a permanent repair, or by replacement), can be modelled by a Renewal Process (RP). Historical damage data of part 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. Figure 4.2a gives a more detailed breakdown of these cost types. In short, repair cost is

associated with the damage rectification, directly related to the type of damage. Whereas aircraft grounding cost and disruption cost are indirect, dependent on the situation at the time of damage, which limits their use as consequence in Chapter 2 and 3. These indirect cost include the immediate handling of an aircraft that may not fly due to the damage or the network effects of the grounded aircraft: cancellation cost or an aircraft swap may be involved [60, 61]. 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 while the aircraft is grounded are taken into account (see Figure 4.2b). The time needed for grounding the aircraft and perform individual tasks is established via internal data sources, again yielding precise estimates.

Then using the individual criterion rating system, all the options are normalised and compared to each other per individual criterion.



(a) Total cost breakdown (b) Total downtime breakdown

Figure 4.2: Cost and downtime breakdown for MCDM evaluation

5. **Option evaluation** (WSM): the WSM 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 Subsection 4.3.2, and with a systematic global weight search all weight cases are explored in Subsection 4.3.3.

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.

4.3.2. CASE STUDY RESULTS

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

OPTION IDENTIFICATION

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 factors considered:

1. **Station of repair**: Where is the aircraft located at the moment the damage is found?
2. **Availability of permanent repair facilities**: Are the facilities for permanent repair available?
3. **Temporary repair possibility**: Is the 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?

Table 4.1: 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**

Each of these factors are Boolean with only two possible answers, presented in Table 4.1 are also the selected settings of the case study highlighted in bold. This narrows down the BDT to account for feasibility of repair options in relation to operational and logistical constraints. 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.
- **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 (Temp → Perm, or Temp → Spare, or Temp → Lease).
- **Aircraft swap availability**: no aircraft was available to swap-in and operate the scheduled flight.
- **Spare part availability**: a spare part was available in the form of a 'cannibalised' 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**: a lease part was available. 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.

With the factors defined and motivated, five possible operational process options for the outboard flap can be identified. These options are also dependent on two future maintenance slots for the aircraft where follow-up actions can be conducted, occurring at 30 and 40 flight cycles (FC) after the damage. The resulting options for repair are shown in Table 4.2.

All options start with a temporary repair at the moment of damage identification (0FC). 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 30FC whereas option 2 executes the action at a later time, 40FC.

Table 4.2: Feasible repair options for the case study settings

Maint. options	Considered time horizon in flight cycles (FC) for maintenance options		
	0FC	30FC	40FC
1	Temp repair	Perm repair	-
2	Temp repair	-	Perm repair
3	Temp repair	Spare install with perm repair on original	-
4	Temp repair	-	Spare install with perm repair on original
5	Temp repair	Lease install with perm repair on original	Remove lease and install original

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 30FC and 40FC 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 30FC. 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 40FC the lease is removed to be returned to the vendor and the original flap is re-installed 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 4.4 for more details).

CRITERIA RATING

With the repair options identified, they have to be evaluated for survivability, cost, and downtime.

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 utilisation from 2006 to 2015, with 96 damage occurrences for the system under consideration. The NHPP was modelled using a power law process [62], whereas the RP was modelled using an underlying Weibull distribution. The airline allowed for using the Weibull parameters (η = 1459, β = 1.19, with Chi-Squared goodness-of-fit test p-value = 0.76) for model development. However, the actual frequency of repair values have to be held confidential, hence the details regarding parameter estimation are omitted from this analysis; the procedures followed are compliant with classical reliability theory [62], and details of sequential survivability can be found in Appendix B.

The long term survivability is summarised in Table 4.3. Survivability should be maximised 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 4.2, the rating is calculated to be 0.21. A decision based solely on survivability characteristics would prioritise option 5.

Cost All cost have been combined together as singular value. While the actual cost figures cannot be provided due to confidentiality, the total cost criterion rating of each option is stated in Table 4.3. Note that cost should be minimised and by using Equation 4.3 the cheapest option can be expressed with the rating of 1.

Options 3 and 4, involving the swaps, have the lowest cost because grounding related cost is 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 of 0. Options 1 and 2 are more expensive than the cheapest options; using Equation 4.3 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 minimising cost, but option 1 and 2 are close contenders.

Downtime Similarly to cost, downtime of 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 declared in Table 4.3. Note that downtime should be minimised 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 favourable options. Though being the most expensive, option 5 is in the middle when considering downtime, and receives a rating of 0.5.

	Survivability	**Cost**	**Downtime**
Option 1	0	0.89	0
Option 2	0.21	0.89	0
Option 3	0	1	1
Option 4	0.21	1	1
Option 5	1	0	0.5

Table 4.3: Long-term individual criterion rating ratings for feasible maintenance options

MAINTENANCE OPTION EVALUATION: EXAMPLE OUTPUT

Having obtained individual criterion ratings, the aggregated scores for the feasible maintenance options is determined by the criteria weights. In Subsection 4.3.3, a systematic sensitivity study is performed to analyse the influence of weight settings on decision model outcomes.

Here, an example case is presented resulting from WSM model. For this case, the criteria are given the same weight of 0.333. The resulting aggregated scores based on this set of weights are visualised in Figure 4.3.

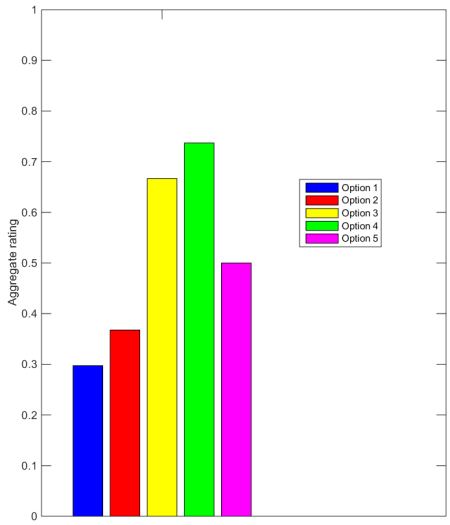


Figure 4.3: Aggregate rating of all options for example case (equal priority of criteria)

Option 4 is calculated to be the best option if a decision-maker values each criterion equally. Despite scoring relatively low in survivability, option 4 outperforms the others because of its performance in cost and downtime. In the real life case the maintainer also chose option 4, as detailed in Section 4.4. A drawback of this presented example provides detailed insight into the MCDM model sensitivity to weights. To this end, a sensitivity analysis has been performed on the weights.

4.3.3. 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. Due to the small number of decision criteria, a global search of entire weight assignment space is feasible, leading to full exploration of weight cases. 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 run time is approximately 5-10 seconds for the global search.

The weight assignment space is explored in the following ways:

1. The space is explored to identify the best option and its respective aggregated rating for any given set of weights.

2. Similarly, the worst option 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 options with respect to weight settings.

BEST OPTION GLOBAL SEARCH

When exploring the whole search space three regions can be identified, related to three best options, as shown in Figure 4.4.

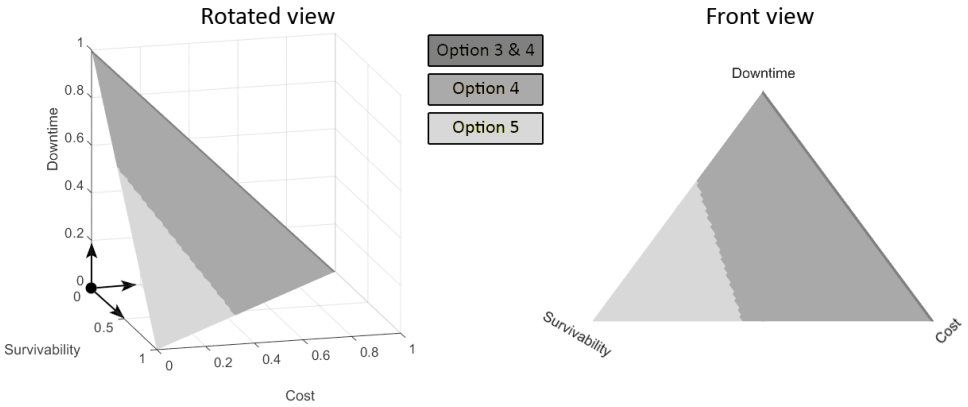


Figure 4.4: Global search result for best option

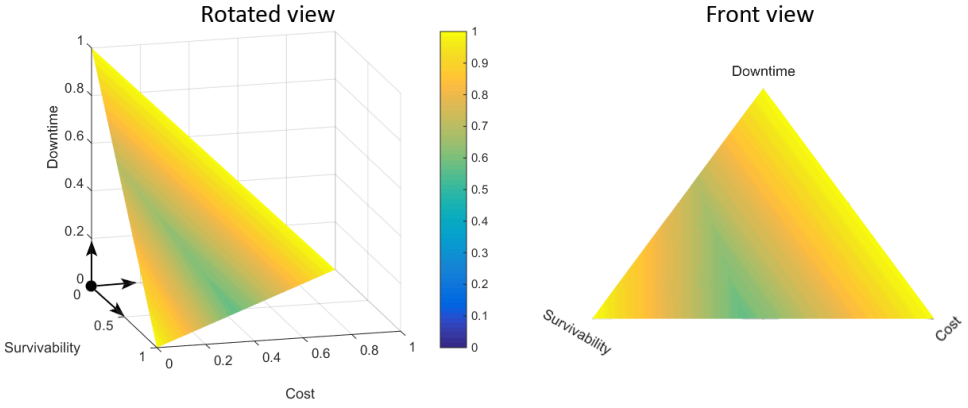


Figure 4.5: Best option rating

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 option. While it is useful to know what the best option would be for a given set of weights, the most important information Figure 4.4 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 see Section 4.4. 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 options 1 and 2 should not be considered.

WORST OPTION GLOBAL SEARCH

The global search for the worst option results in Figure 4.6. Option 1 and 2 are indicated as the worst option for a large part of the search space, which is understandable in the context of Figure 4.4. 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 also 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.

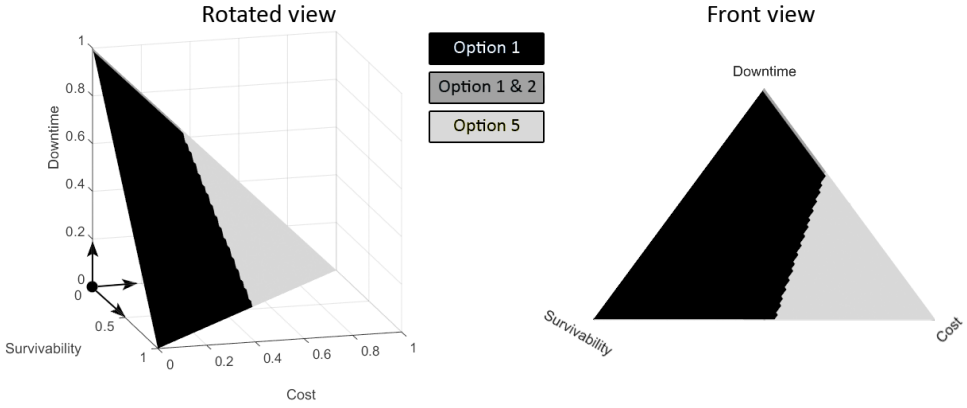


Figure 4.6: Global search result for worst option

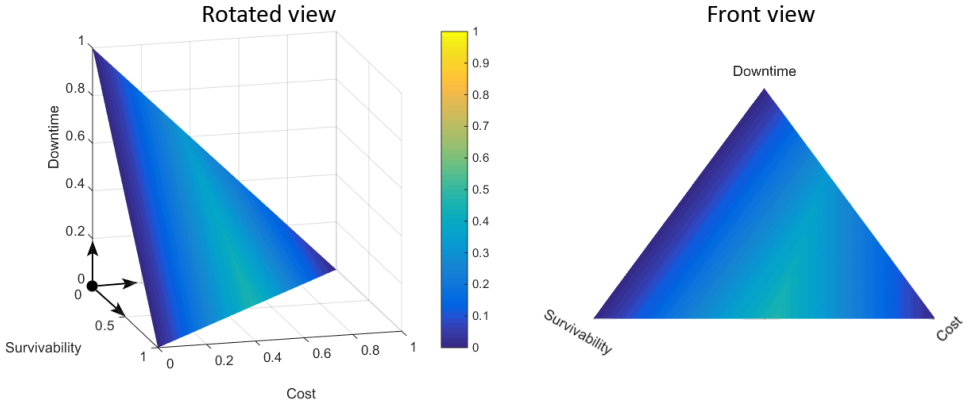


Figure 4.7: Worst option rating

The aggregate rating of the worst options are given in Figure 4.7. It can be seen that in the corners and across the downtime-survivability edge (where the cost criterion weight is 0), the worst option of Figure 4.6 obtains ratings of 0. The worst option rating increases farther from the corners and closer to the border of options 1 and 5 in Figure 4.6.

OFFSET BETWEEN BEST AND WORST

Figure 4.8 shows the difference between the aggregate ratings for the best and worst options for any given weight. In the corners where each of the individual criterion are heavily weighted the offset 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 in that weight space, making it harder to differentiate from each other. Therefore this informs the decision-maker that they need to consider downtime by increasing its weight if they want a clearly distinguished best decision.

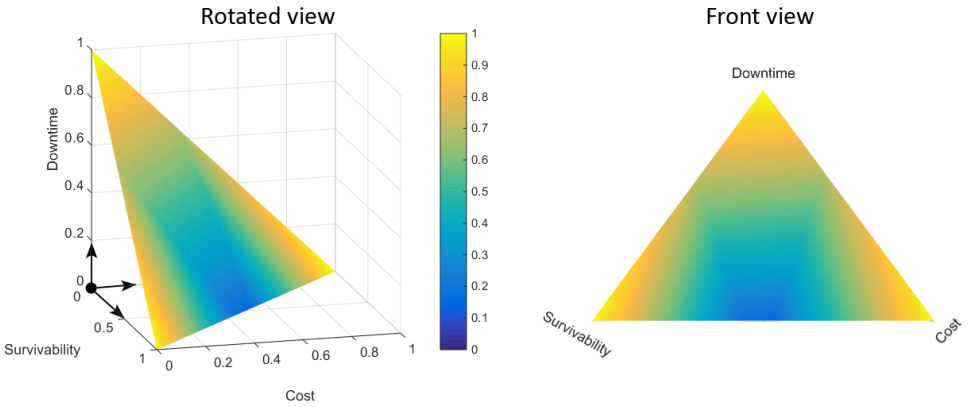


Figure 4.8: Global search delta between best and worst decision rating

4.4. 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.

4.4.1. VALIDATION

In Figure 4.9, a time-line is presented which gives the actual inputs, process steps and outcome of the real-life case.

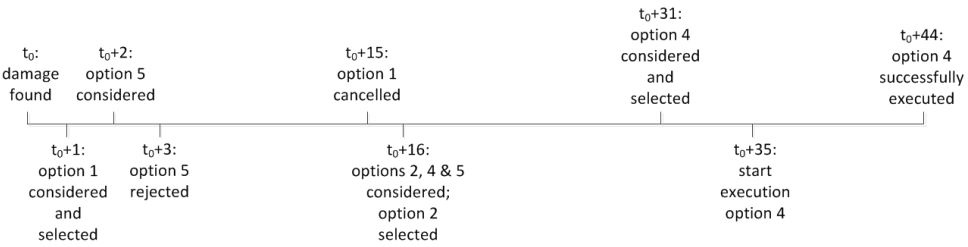


Figure 4.9: Case study time-line, starting at t_0 (damage identification), with increments in stated days

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. The option 5 was considered and rejected two and three days later (t_0 + 2 and t_0 + 3, respectively). The loan option was rejected after receiving the cost information and deemed too expensive. 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, 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, to be performed at a later date in the time-line (similar to option 2). 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 Section 4.3, several aspects are noteworthy:

- 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), but in the considered case, it took 5 weeks for the maintainer to consider that option seriously and select it.

- 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 noticed much later. The lack of a systematic approach allowed for serious consideration of sub-optimal choices, and more favourable 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 Subsection 4.3.2 and 4.3.3, and the consideration of option 2 in week 3, which is similarly unfavourable. The model on the other hand would have identified all the options on day 1, with evaluation being possible days later. Under various weighted priorities, either option 4, option 5 or option 3 would be preferred (as shown in Subsection 4.3.3).

4.4.2. 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 of it was not taken into account initially (e.g., the possibility of executing a swap by coordinating 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. By 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, is the fact that multiple iterations were undertaken for the decision process, involving substantial labour-hours effort from several individuals. If the approach proposed in this study would be followed, the decision making process could be completed in a few labour-hours, with about 30 seconds of computation time necessary when all inputs are available. The actual process consumed substantial labour-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 may offer significant benefits to maintainers and associated stakeholders in resolving maintenance decision making problems at the operational level.

4.5. 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: BDT for option identification and the 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 BDT. 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. However, to make the model more adaptable and generalisable, fuzzy inputs can be utilised 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 BDT, 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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5

AIRMEDT: REPAIR DECISION TOOL FRAMEWORK

*The previous chapters have focused on building the theory behind obtaining historical data and formulating a method for maintenance decision-making. Despite the previously discussed methods being verified and validated in case studies, the research still remains on a conceptual level. Therefore, Airmedt (**Air**craft **M**aintenance **E**valuation and **D**ecision **T**ool) has been developed to demonstrate how the research can be implemented as an end deliverable or product. The architecture designates the key classes needed to operate the tool and was developed in a manner to allow for future expansion to all structures of the aircraft. Furthermore, the tool functionality has been verified using the outboard flap case study, resulting in matching the output of the tool and the previous model. The next challenge for Airmedt is to place it in operations to validate the tool in practice.*

5.1. INTRODUCTION

The previous chapters have covered the data gathering, knowledge capture, and analysis of decision factors to develop a model that can provide the best repair option. While the maintenance decision-making model presented in Chapter 4 is functional, it is not in a format that can easily be implemented into practice. A tool is needed that is capable of executing the previously discussed analysis, without the end-user having to know the intricacies of the model functions. The purpose of the tool is to make the research tangible to the end-user.

The implementation will require a open-source platform, so that it can be easily adopted into practice. Therefore, a decision-making tool called Airmedt has been developed using Javascript and HTML, two programming languages that are widely used in web application development. Knowledge Management (KM) is a broad field that is concerned with leveraging knowledge to improve the operational performance of an organisation [1, 2]. A subset of this field with respect to maintenance in the modern era has been e-Maintainence [3, 4]. Despite the prevalence of information systems that pull e-Maintenance into the forefront, Keen [5] set the fundamentals of Decision Support Systems (DSS) that remain revelant to this day. DSS amongst other approaches was most appropriate due to its focus on what the development and implementation of a tool should entail.

This chapter outlines the context of what a decision support tool should be. The requirements for a decision tool is established, and using the DSS development framework a prototype is designed and constructed. The architecture of Airmedt is presented, and the tool as it is currently built is verified. A vision for further developments and implementation within the organisation is detailed, showing the benefits to the decision-making process by fully integrating Airmedt into the different IT systems.

5.2. CONTEXT OF DECISION SUPPORT TOOLS

In this section the current best practices in decision-making tools and systems are discussed. First, the conventional approaches to decision support are presented. Based on the needs of this research, the DSS framework as outlined by Spraque [6] is chosen. Both the DSS framework and the end-users of the MRO have some general requirements that the tool should fulfil. These requirements will go on to influence the development and implementation of Airmedt.

5.2.1. LEVERAGING KNOWLEDGE

Knowledge management (KM) is an industrial practice focusing on leveraging existing knowledge to optimise and improve operations within an organisation [1, 2]. KM is also multi-faceted, in that not only does it establish the enabling factors such as technology and information systems, but also the tasks and set of activities that are required to capture the best use out of the knowledge. As such KM has been divided into two distinct capabilities (see Figure 5.1): knowledge infrastructure, and knowledge processes [1, 2, 7, 8].

On the one hand, knowledge infrastructure capability is composed of the technology infrastructure, the culture and structure of the organisation [1]. Technology in a KM

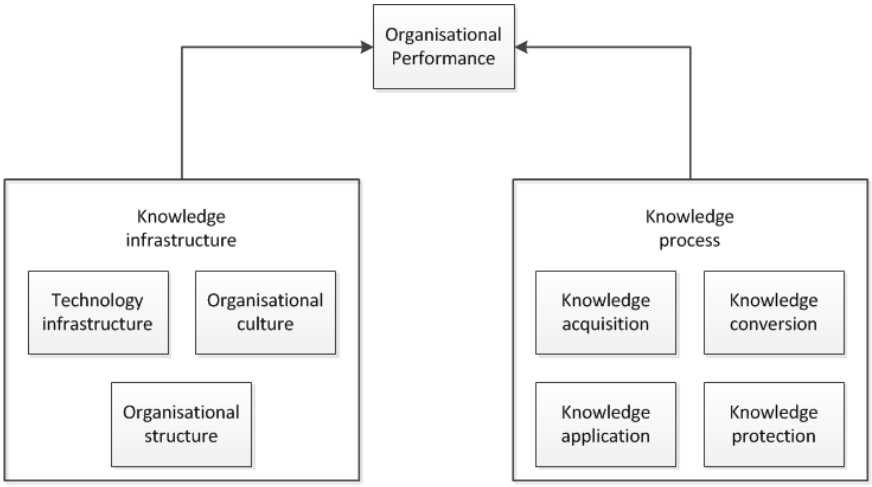


Figure 5.1: Knowledge management capabilities [1, 2, 7, 8]

context mostly refers to the dedicated IT systems within an organisation. These systems enable the creation and sharing of knowledge within a defined network. Organisation's culture is the overall behaviour and values of the individuals and departments that make up the organisation's structure. These values can be encouraged or enforced through rules and regulations within the hierarchy of the organisation. For the purposes of developing Airmedt, the organisational culture aspect of the knowledge infrastructure capability such as valuing safety, increased performance, communication, and efficiency, is assumed to be well established. The aspects that concern the tool implementation are technology infrastructure, and organisational structure influencing communication among different stakeholders in the decision-making process.

On the other hand, knowledge process capability consists four aspects: knowledge acquisition, conversion, application, and protection [1]. Most of these aspects have already been addressed in the previous chapters. For instance, knowledge acquisition is concerned with accumulating all information that an organisation has access to. In the case of this research, the knowledge needed are the operational conditions, the historical damage data (or the lack thereof addressed by the deductive-inductive process), and the repair manuals. The acquired knowledge have been converted into useful formats such using Boolean scenario tree and operational constraints to determine maintenance scenario, statistical analysis on the damage data for rate of occurrence, and establishing the repair actions from the SRMs. Although the models that apply this knowledge to create value has been developed in Chapter 2-4, Airmedt will be the end-product that users will see and use. Hence, how the knowledge will be applied in practice is addressed in this chapter. Finally, certain pieces of information are confidential to the MRO and so must be protected to ensure their competitive advantage. Therefore the four aspects that require further exploration in the development and implementation of Airmedt are technology infrastructure, organisational structure, knowledge application, and knowledge protection.

5.2.2. DECISION SUPPORT SYSTEM (DSS) FRAMEWORK

e-Maintenance is an expanding field that leverages knowledge specifically for maintenance applications [3, 4, 9–11]. The applications are broad assisting in maintenance strategy development, maintenance planning, condition-based maintenance, prognostics, diagnostics, and more relevant to Airmedt, maintenance support. Specifically, Airmedt aims to provide support for maintenance decision-making. Hence, DSS will be explored, defining the framework requirements.

One of the first instances of Decision Support Systems being discussed from a research perspective was established by Keen [5] in 1980. Still the fundamentals [5, 6] of the report find relevance through the years to this day in decision-making processes [12–16]. Spraque [6] states DSS as being *"dedicated to improving the performance of knowledge workers in organisations through the application of information technology."* This focus directly suits the tool's need to explore technology infrastructure and knowledge application.

An ideal DSS must have four characteristics to be successful [6]:

1. Take an unstructured problem and present it in an understandable manner

   Rearranging the relevant information such that the user is aware of the core problem. The unstructured problem in the case of Airmedt is the collection of constraints and variables involved to identify a scenario and evaluate repair options.

2. The different models and techniques coordinate together

   The analysis performed must be linked such that the appropriate functions are called when needed. These links and functions are vital to the architecture of the tool.

3. Intuitive to use by anyone with basic understanding of computers

   The user cannot be expected to be proficient in programming languages or syntax, and so a Graphical User Interface (GUI) is needed to increase the flow of the decision process through direct interaction. This influences the construction of the tool.

4. Design must be flexible for future use and adjustments

   DSS development is most often not finished in a single instance, instead it is an iterative or adaptive process.

These characteristics of DSS can be scaled at different levels of complexity, namely specific DSS, DSS generator, and DSS tools [6]. Specific DSS is the smallest scale where a system has a focused application or function that it performs. Conversely a DSS generator is a more general version of a support system, it is a package that can be easily adapted to develop a range of specific DSSs. Lastly, DSS tools is the complete collection of hardware or software needed at the most fundamental level to develop a specific DSS. The DSS tools can include operating systems, programming languages, and any supporting software. Airmedt, will be discussed at the specific DSS level because it was developed using license-free programming languages (HTML and JavaScript) and off the shelf hardware (Dell laptop). Additionally, Airmedt has a specific function of assisting in

maintenance decision-making, and so there is no requirement for developing a generic version.

DSS development typically involves multiple roles taken on by individuals or departments, these include: management, intermediary, DSS builder, technical supporter, and tool-smith [6]. The management is the team that makes the final decision on a repair problem. They often consult with a single or multiple intermediaries that assist in the decision-making by giving advice on the problem. The DSS builder and technical supporter is currently myself. I'm in charge of building the actual tool in consultation with the stakeholders. I'm also the technical support because I'm the sole person familiar with the functions and models implemented in the tool. However, in the future when Airmedt may be implemented, then the IT departments will be major part of the technical support group as they would have expertise on how best to integrate the relevant data systems. Lastly tool-smiths work at the most fundamental level on the DSS tools, but because license-free programming languages are being used, in this case there is no one taking on this role to influence Airmedt's development.

5.2.3. USERS AND FUNCTIONAL REQUIREMENTS

Decision-making will involve multiple departments within and outside of the MRO. The stakeholders in decision-making can be generalised into four groups with defined roles: maintenance shop, Maintenance Control Centre (MCC), Operational Control Centre (OCC), and external vendors. This research has been in direct collaboration with the maintenance shop. Therefore, Airmedt has been first developed from their perspective, taking on their requests to ensure that the prototype tool functions to their current needs. However, in the future implementations the other stakeholders will play a critical role and will have their own unique requirements (see Section 5.4 and Appendix C).

Maintenance shop (Intermediary): This group is in charge of inspecting any reported faults and formulating the appropriate actions. They also conduct the final repairs and make sure they have enough stock of relevant parts. While the maintenance shop is essential to the decision-making process because they are closest to the damage, they are not the final decision-maker. Instead, their role is of an advisor and executor of repairs.

Primary requested tool requirements for initial prototype

- Easy to interact and navigate
- Simple and clear input fields for estimates related to time, cost, and other operational constraints
- Clear indication of the different options, and the steps involved in the options
- Results for best options easy to interpret, and if needed further breakdown of the analysis
- Ability to save the results to be used in consultation with other stakeholders

Requirements for future version of tool

- Able to receive notification of damage on aircraft

- Receive overview of resources such as availability of labour, machining, materials etc.
- If certain resources need more information (such as cost and availability) then be able to send requests to appropriate parties
- Once analysis is conducted the set of options is sent to MCC along with an indicated preferred option and why
- Ability to consult with other parties to ensure the details are correct and not conflicting
- Receive final decision from MCC
- Able to confirm the repair execution

Maintenance Control Centre (Management): The MCC is in charge of the maintenance scheduling for the fleet of aircraft. MCC is the final decision-maker choosing the option, although in practice it is a collaborative process making sure a consensus among stakeholders is reached.

Operational Control Centre (Intermediary): The OCC is essentially the customer of MCC and maintenance shop. They are in-charge of operating the fleet of aircraft in their network

External vendors (Intermediary): While the maintenance shop is in charge of stocking, some parts require too much capital to be stocked. Therefore, external vendors act as suppliers providing services when asked but are not involved in making the final decision.

5.3. TOOL DEVELOPMENT

The development approach can either be iterative or adaptive [5, 6]. Iterative approach cycles through a process with four steps: analysis, design, construction, and implementation. In an iterative approach it is implied that at the beginning of the cycle there is no DSS, and the development starts from scratch. By looping back at the different steps of the process, discrepancies are identified and improved upon. Meanwhile, adaptive approach assumes that there is already a proven tool or DSS that has been used for another application. Therefore, the adaptive process simply takes that existing version and modifies it to the new use case. For Airmedt an iterative approach is applied since to the best of author's and the contributing MRO organisation's knowledge there is no openly available tool that meets all the requirements discussed.

Analysis involves looking at the design problem, objectives, and user requirements to establish the needs of the tool. This has been executed already and discussed in the context of Airmedt in Section 5.2. As a result of these requirement the architecture of the tool is discussed in Subsection 5.3.1. Then when coded and compiled the tool is

built/constructed and ready for initial use. Implementation is putting the tool into practice into daily operations. While Airmedt has not yet been fully implemented (see Section 5.4 for implementation plan), it has been verified against the maintenance decision-making model case study in Chapter 4.

5.3.1. TOOL ARCHITECTURE DESIGN

A Unified Modelling Language (UML) class diagram of Airmedt shown in Figure 5.2 visually depicts the architecture of the tool. This architecture is simplified from the perspective of just the MRO (MCC and Maintenance shop) and OCC, excluding any external parties. Through this diagram the relevant classes and their interactions are defined. A class can represent a person, a part of an aircraft, or a collection of actions and information. There are three elements to define a class (see Table 5.1): name, attributes, and operations.

Table 5.1: An example of class and its content

Class name
-attribute1: string +attribute2: object
-operation1(): string +operation2(): object +operation3(): bool

The name is simply for identifying a class, generalised enough to represent all the attributes and operations it encompasses. Attributes are the variables or values the class has access to, and can be in the form of string, object, Boolean, etc. Operations are the actions or functions executed by the class, and they return values in various forms as well. The visibility of the attributes and operations are indicated by symbols, − for private and + for public. Different visibility conditions can be present in the same class because the attributes and operations are split between client- and server-side. The client-side is everything that the user can directly access or interact with from the tool (hence public). Contrarily, server-side keeps all the values and functions that the user needs but cannot directly manipulate because the information is either confidential or if tampered could lead to bugs and false analysis.

User: The UML diagram begins with User parent class, defining the attributes and actions needed for a user to log into Airmedt. Once the username and password combination is confirmed, the tool is made accessible. Multiple child classes are created, all inheriting the attributes and operations of the User class. The child classes represent persons or entities (maintainer, Operational Control Centre (OCC) employee, Maintenance Control Centre (MCC) employee) that would have their own profile details. Ideally each profile would have unique rights and operations but currently every user can access the same functions and are associated with the Parts class. Refer to Section 5.4 for indications on how the child classes may change.

Part: The next parent class in the architecture is called Part. The purpose of this class is to load the different structures of an aircraft and allow the user to select the one they wish to conduct a multi-criteria evaluation. There are four child classes representing

the major ATA structural groups of the airframe: wing (ATA 57), fuselage (ATA 53), nacelle (ATA 54), and tail (ATA 55). Furthermore, these four parts have their own set of sub-part child classes, each representing a sub-ATA. For simplicity of demonstration, only the wing child classes have been expanded in Figure 5.2. The sub-part child class includes all the Boolean scenario questions unique to that sub-ATA. There has to be unique sets of questions because certain actions cannot be performed on particular sub-parts. For instance, in Chapter 4 an outboard flap could be replaced with a spare, but if a fuselage section is damaged then it is not possible to replace a whole section. Hence, some Boolean scenario factors do not apply to all sub-parts.

Scenario evaluation: Once the part has been selected, the Scenario evaluation class executes a series of operations to collect all the relevant data. The scenario based on user input is defined, and all other inputs related to cost or time are organised. After a check to make sure all the required inputs are present and converted into the right format, the class processes the data on the server side. The options are evaluated privately on the server side to keep certain variables related to the MRO confidential. Once the calculations are complete the option results are returned to be displayed for the user.

Calculations: The Calculations class is on the server-side communicating with the client-side to obtain all the necessary information to calculate the cost, downtime, and survivability of each options. The class consists of two operations called nhpp() and rpProb(), which calculate the survivability over time for each option. The statistical analysis of impact damage occurrence in the historical data and in the pseudo composite dataset directly contribute to these two operations. The additional child classes are executed based on the options identified. If for instance there is an option to perform temporary repair followed by permanent, then the tempPerm() operation of the Permanent child class would be executed.

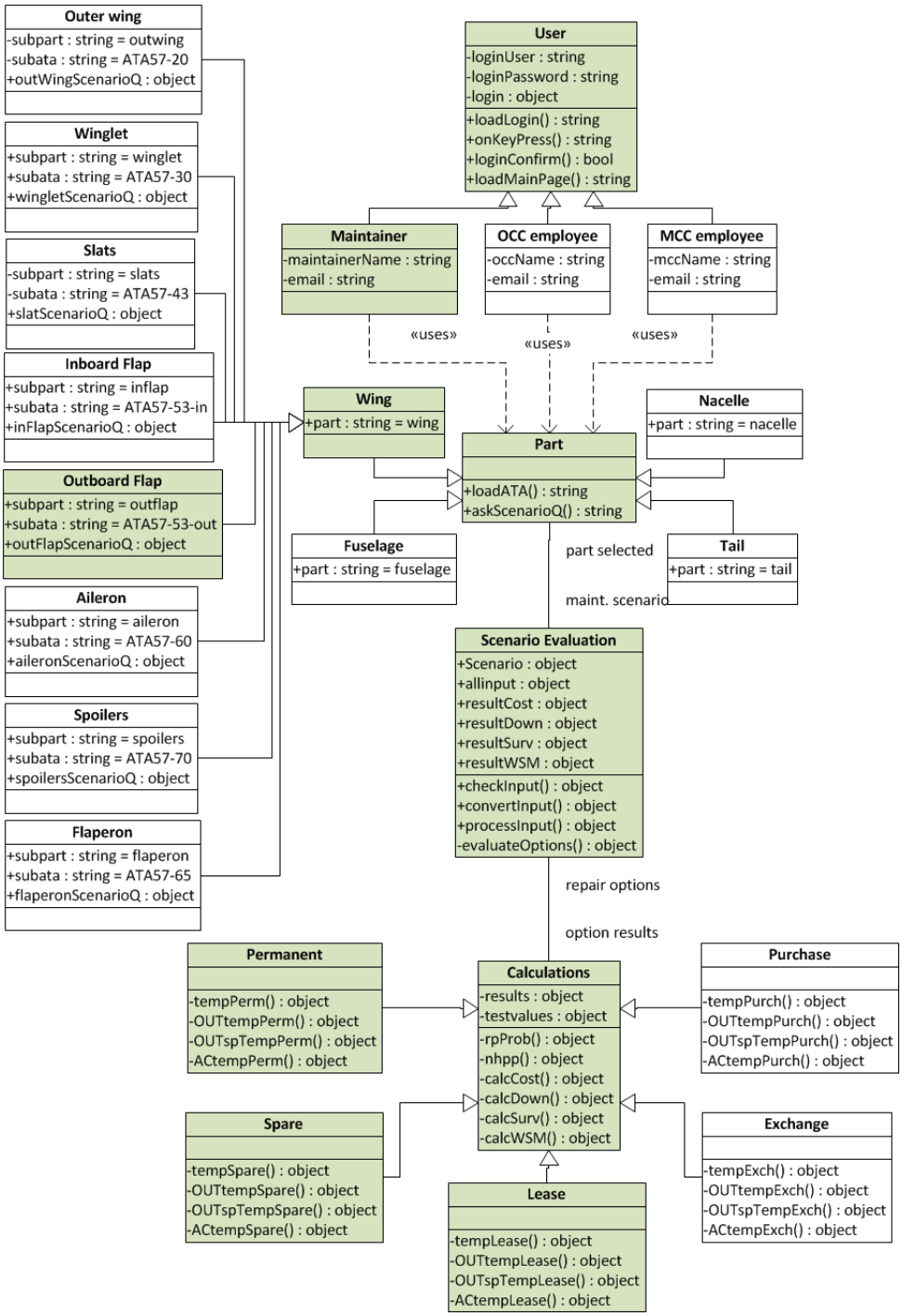
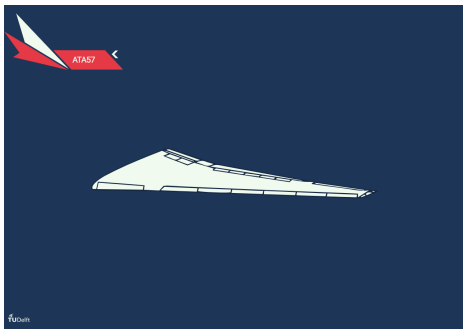


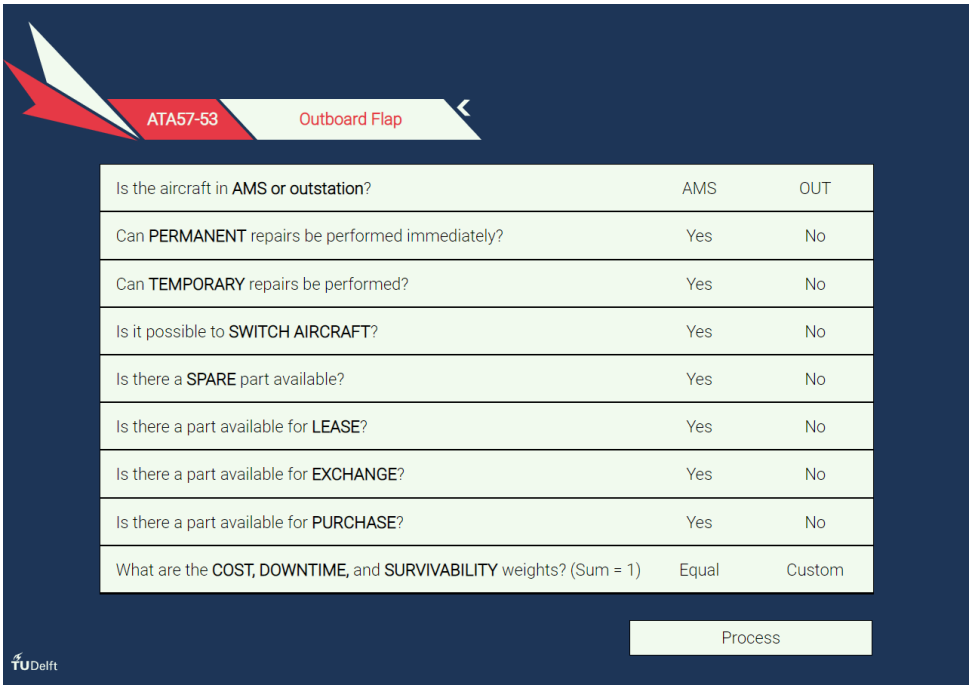
Figure 5.2: UML class diagram of Airmedt

5.3.2. CONSTRUCTION OF CURRENT VERSION

(a) Airmedt home



(b) ATA57 Wing selected



(c) ATA57-53 Outboard flap selected, and the relevant Boolean scenario questions are prompted

Figure 5.3: Airmedt tool

Airmedt has been implemented as an web application accessible using any internet browser, or downloadable as an app for smartphone and tablet. Figure 5.3 shows the current version of the tool. Beyond confirming that Airmedt is functional, the tool was constructed to be intuitive with a clear step-by-step GUI. Therefore, once the user is logged in they will see an aircraft that is interactive (Figure 5.3a). The airframe consists of the four selectable structural parts discussed in the architecture of the tool (Figure 5.2):

wing, fuselage, nacelle, and tail. By clicking on a major structure such as a wing, a more detailed interactive figure is displayed to select the sub-ATA chapter the user wants (see example Figure 5.3b). Continuing with the example of the Outboard Flap, once selected the relevant Boolean scenario factors and criteria settings are prompted for the user to input the scenario details (Figure 5.3c). The bold Boolean scenarios factors are easy to identify, each with only two selectable answers. The inputs are asked in a question form to ensure that the user is not confused and knows exactly what is being asked of them.

5.3.3. TOOL VERIFICATION

To verify the functionality of the current implemented version of Airmedt some of the options from Chapter 4 are evaluated. These options include an example of temp-perm, temp-spare, and temp-lease, specifically options 2, 4, 5 respectively. Airmedt output the same results as the Multi-Criteria Decision-Making model case study shown in Figure 4.3. As Figure 5.4 indicates there are other tabs for detailed analysis of the options. Due to time restrictions, global search plots such as the one shown in Figure 4.4 has not been implemented. The important aspect to be verified is that Airmedt provides the same analytical results as the Matlab code, which it does exactly. Additionally Figure 5.2 indicates the relevant classes (coloured in green) that have been executed to perform the options evaluation.

Figure 5.4: Airmedt verification results

5.4. TOOL IMPLEMENTATION

The final step of the iterative process of developing a tool is implementation. The current version of Airmedt is a standalone tool, requiring manual inputs into the tool for analysis. This is cumbersome especially if a lot of options are available. The major step needed for Airmedt to fully reach its performance potential, is to be integrated with the information systems or servers of the MRO's various departments. Furthermore, to aid the integration the different user types and their functions needs to be increased and defined for the future version.

5.4.1. INCREASED USER FUNCTIONALITY

An aspect to develop in the future is to create unique types of user classes that have their own defined roles with respect to decision-making in Airmedt. Decision-making will involve multiple departments within and outside of the MRO organisation as shown by the different stakeholders involved in Subsection 5.2.3. Accounting for each user's requirement (Appendix C) the unique operations that they can execute are shown in Figure 5.5. Updating these relations between the stakeholders and the increased integration with the information systems would lead Airmedt to be smoother because the communication among the stakeholders will be on need-to-know basis rather than being under- or over-informed (see Figure 5.7).

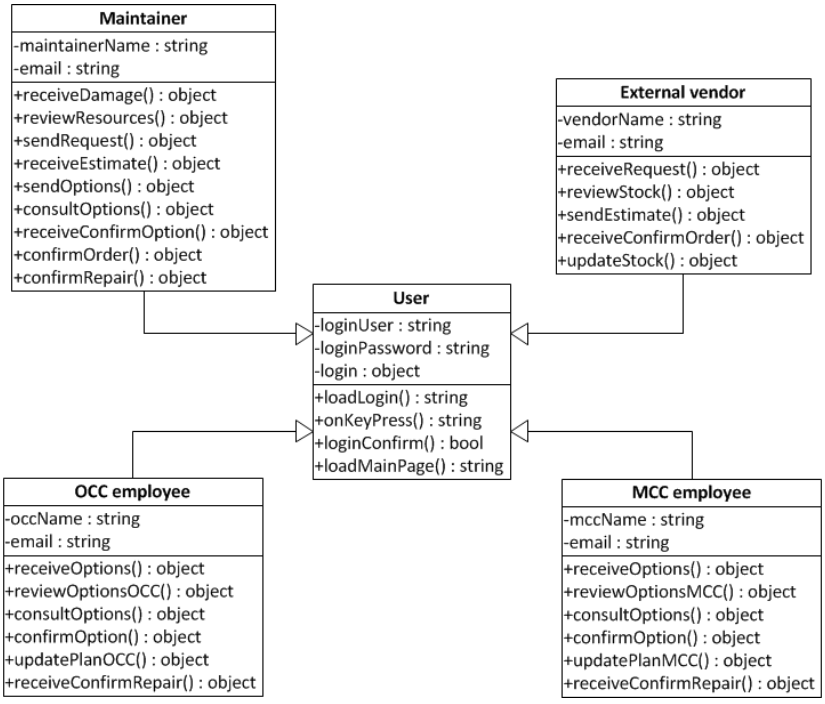


Figure 5.5: Changes to User operations in Airmedt architecture

5.4.2. SYSTEMS INTEGRATION AND OPERATIONAL IMPLEMENTATION

Taking Airmedt from a stand-alone tool to full system integration is going to require coordination with all stakeholders. Each of them have rights over their own data with no obligation to share due to confidentiality or security.

As a result of the different data rights, a conflict of interest is introduced where Airmedt server is forced to be an independent entity but cannot function without the data of the stakeholders. Therefore, each group will need to decide what information they are willing to explicitly share with the Airmedt system. In order to ensure Airmedt does not interfere with the operations or databases of the stakeholders, Airmedt server must have read-only rights on the information being shared. On the server-side the information gathered is organised to be presented on the client-side. The Airmedt server and client will be exchanging data whenever a decision is being investigated. Each stakeholder will have an employee or team responsible for interacting with Airmedt to execute the decision-making process. The overall integration and the separation of different entities are shown in Figure 5.6.

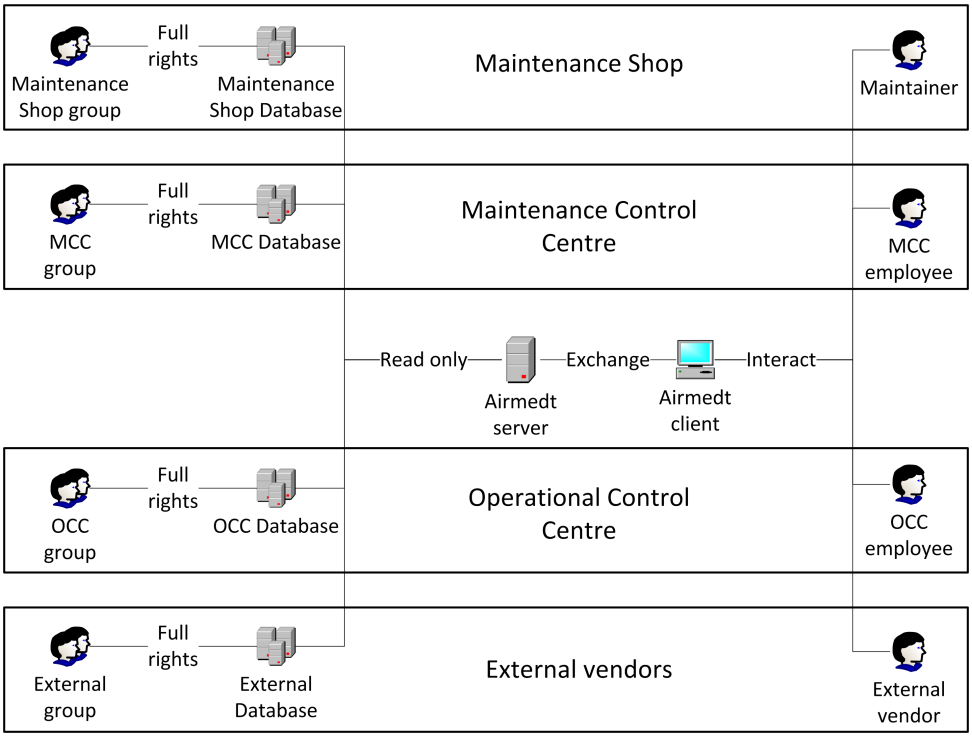


Figure 5.6: Database and network integration

When Airmedt is integrated and implemented, the decision-making process will involve all parties through the Airmedt client. This decision-making process of different operators the individual users execute (see Figure 5.5) is summarised in Figure 5.7. Operator 1 begins with the maintainer receiving an unplanned task. They execute the Airmedt

tool to evaluate the scenario and obtain the best repair options from the Airmedt server. Operator 2 is optional, to review the internal resources of the maintenance shop. It should be noted that the Airmedt server is connected to stakeholder databases but since the maintainer is part of the maintenance shop they can have direct read-only overview of the Maintenance Shop database. This optional operator is similarly replicated for the other stakeholders (operator 5, 10, 11). The maintainer may notice that some of the parts or machining tools are not in stock and therefore can execute a request to external vendors. Upon receiving the request the external vendor reviews their stock and replies back with an estimate. With all information in hand and analysis executed, the maintainer finally sends the repair options to both MCC and OCC.

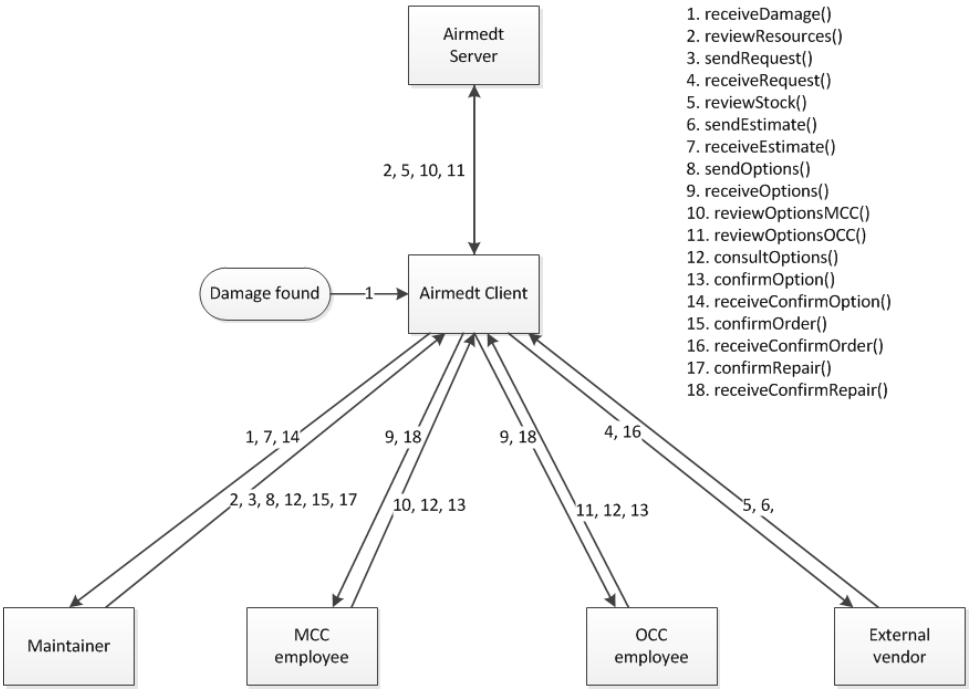


Figure 5.7: Decision-making process through Airmedt client

The MCC and OCC is notified of the problem along with a preferred course of action with estimated cost and time. The MCC takes it into consideration confirming whether the option can fit within the maintenance schedule. Similarly the OCC wants the aircraft fleet to be operating at full capacity, and any unplanned maintenance would disturb their network planning and flight schedule. If there is a discrepancy, then the MCC will iterate on the options with the maintenance shop and the OCC until all parties agree and confirm an option. The maintenance shop receive the confirmation on an option and begins to execute the plan. If need be the external vendor will be contacted by the maintainer to confirm an order on parts or services. Once the damage has been repaired the MCC and OCC will receive a final confirmation of repair completion.

Two operators have been excluded in the decision-making process, updatePlanMCC() and updatePlanOCC(). These operators are intended to adjust any network planning or maintenance on a strategic level. However, the tool is scoped to corrective and unplanned tasks. The proposed operators, while potentially useful for MCC and OCC to directly update their plans, may be exceeding the scope. If implemented it would be one of the last stages when all other networking and execution processes are stable.

Taking the technology further with the introduction of drone-based inspections and automation, there can be a whole eco-system around decision-making (Figure 5.8). Future inspections technologies can directly notify the relevant decision stakeholders with the information they require. Then based on their own analysis and consultations with other parties through Airmedt, a final consensus on a decision can be reached in a streamlined fashion.

In this manner a lot of the information gathering such as cost estimates, resource availability, and schedules can be automated in the background requiring the user to only select the Boolean scenario factors. In fact, there is even the possibility to automate Airmedt to pre-select the scenario factors based on the information it has access to, allowing the user to take faster action.

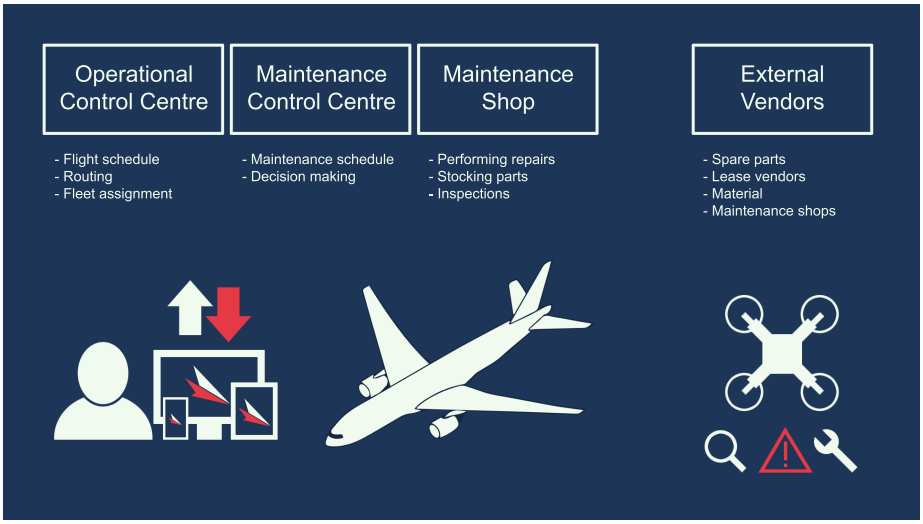


Figure 5.8: Vision for future decision-making eco-system

5.5. CONCLUSION

Airmedt has been built to demonstrate the research in action and make the decision-making model more tangible for future adopters. The tool must be able to leverage knowledge to assist the decision-making stakeholders in understanding the factors involved and selecting the best repair option. A form of e-Maintenance called Decision Support Systems (DSS) provided the framework on which Airmedt has been built. The development was an iterative process involving the maintenance shop as the primary user for the initial prototype.

An analysis of requirements was conducted from a development perspective. For development, it was important that the tool was designed to be future proof. The architecture of the tool is such that it is easily scalable. The class-based approach means that any new features can be added on as a new module of operators and attributes that can communicate with the existing architecture. The technology infrastructure for the current version of Airmedt has been kept simple using off the shelf equipment and license-free programming languages such as HTML and JavaScript. Furthermore, the tool has been verified using the same case study from Chapter 4, and the results of Airmedt were the same.

Additionally, the end-user requirements were also defined by the maintenance shop as they were the main collaborator in the prototype built. Apart from accurate knowledge application in the evaluation operations of Airmedt, their requirement focused mainly on the user-friendliness of the tool. Airmedt needed to be easy to interact and navigate, with clear inputs and output results. Hence, the client-side is designed to be intuitive to use by making it interactive and simplified where possible. All of the calculation operators were placed on the server-side to keep them protected and to ensure that the user only deals with the inputs and outputs. With future integration with other data systems, other stakeholders will also be able to use Airmedt and interact with each other to reach a consensus on the final option.

The next phase of Airmedt is to validate the tool in practice. The response from industry experts has been positive, clearly indicating the potential usefulness of such a tool. However, to truly reach this potential, Airmedt needs to be integrated with information systems in the MRO. The current standalone version of Airmedt means that the user still needs to first look for the information before using the tool. If integrated, the information gathering process can be automated in the background. Another aspect that Airmedt needs to be improved upon is to create a diverse set of users that have unique responsibilities when interacting with the tool. To implement Airmedt will require collaboration between multiple departments to understand every stakeholder's need.

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6

CONCLUSION

6.1. REVIEW OF OBJECTIVES

Six objectives are introduced and addressed over the course of this dissertation. In this section the objectives and the final conclusions reached from the research are reviewed.

1. Deduce the impactor characteristics (size and energy) based on the dent dimensions (length, width, depth) on aluminium structures

Chapter 2 focused on the threats that are expected to impact a typical wide-body aircraft. Given the right impactor characteristics (size and energy) an impact event on a structure can cause circular or elliptical damage of certain dimensions (length, width, depth). Therefore, the impactor characteristics are proposed to be predictable if the properties of the target plate and the final damage dimensions are known. This deductive process was conducted in a case study for an aluminium Al2524 plate using the fuselage damage data of a Boeing 777 fleet. Based on quality of the data (accuracy, consistency, and completeness), 120 instances of damage were chosen from a fleet of aircraft that operated over a period of 10 years. Of the selected damage 110 are successfully deduced. The impactor radius and energy are in the range of 1-236mm and 1.5-109J respectively, and both followed a 3-parameter Weibull distribution. Overall the objective of deducing impactor characteristics is achieved with some exceptions.

2. Induce the damage onto composite structures to predict the damage dimensions (length, width, depth) and damage type, to create a composite pseudo damage dataset

The second objective explored in Chapter 3 extends upon the findings of the deductive process. The inductive process takes deduced impactor characteristics to induce damage on a composite plate to predict future damage that could occur under similar conditions. The assumption of similar conditions is motivated by the similarity in operations, size, and shape of Boeing 777 and 787 aircraft. The induced damage results are

categorised as followed: 25% no dent, 54% residual dent, 4% initial fibre breakage, 18% penetration. As can be seen in the results, an impactor causing a dent on an aluminium structure can cause a broader range of damage types in composites with different dimensions, or even not cause a damage at all. Hence, the objective of inducing damage using deduced impactors to create a composite pseudo damage dataset is achieved, although specifics of damage modes can be expanded upon.

3. Obtain the likelihood and consequence of impact events for the composite pseudo damage dataset, to inform the decision-making evaluation of repair options

Chapter 2 utilised the impact damage data to evaluate the risk of impactors on aluminium aircraft. Similarly, Chapter 3 conducted the same risk analysis but from both material perspectives. The risk likelihood is directly obtained by the rate of occurrence of impactor characteristics. The consequences are determined as the actions that are required as a result of the impact event: no repair or minimal temporary repair (low-consequence), and heavy permanent repair (high-consequence). Both types of consequence are quantified in terms in direct repair cost-ratio (4:1), where high-consequence events lead to four times more expensive repairs than low-consequence. Taking the penetration limits of composites as the boundary between the low- and high-consequence led to differences in risk between metal and composite materials. The highest risk of impact for composites occurs for impactors <50mm in radius and up to 150J. Although, due to higher likelihood, impactors as large as 100mm can still pose a risk. Not only is the likelihood of impact determined but the type of repair consequence of the event is also predicted, and thereby informs future repair decisions.

4. Identify all feasible repair options for a structural damage, constrained by operational factors

The knowledge gained from structural damage is intended to be applied for maintenance decision-making as discussed in Chapter 4. A common issue of decision-making in operations is that the constraints influencing the options are not readily available or clear to the decision-maker. This led to the development of the systematic approach to option identification based on Boolean Decision Trees. For each instance of damage a maintainer consults a list of recurring operational and repair constraints. These constraints are reformulated into questions that can only be answered in a Boolean format. Once they are answered the particular scenario is formalised and the associated repair options are identified. Therefore, this simplified process enables the decision-maker to account for all operational conditions, such that all options are identified. The Boolean scenario identification process has been validated against a case study. The real-life process took several days to identify the possible repair options, whereas the proposed approach would be more thorough and take a matter of minutes at most. Additionally, the approach identified an option that was not considered in the real-life case because of the slower identification process that depended on communication through e-mails. Therefore, developing a systematic approach to identify all feasible repair options is successfully achieved with no caveats.

5. Evaluate the repair options based on decision criteria and quantitatively compare the alternatives to select the best option

The identified options are evaluated in Chapter 4 based on criteria: cost, survivability, and downtime. The literature is extensive on decision-making analysis, with each method ranking options in a different manner. From a pragmatic point of view to encourage adoption of the method in practice, the ease of understanding of the underlying analysis is important. Therefore the Weighted Sum Method (WSM) is chosen due to the simplicity of assigning weights to criteria to convey decision-maker preference. This proven method has been expanded upon by developing a global weight search algorithm. Through this algorithm every possible combination of weights for the criteria are tested to analyse which options would be identified as best. When tested on a case study for an outboard flap repair, the global weight search indicated that 2 of the 5 options would never be considered for best option. This form of elimination can save crucial amounts of decision-making time by avoiding in-group discussions over feasible but non-ideal options. Furthermore, the algorithm can further streamline the decision-making process especially if there is an extensive list of feasible options. The run-time of the algorithm depends on the resolution of the weight search, which in the case study was <1min with a resolution 1% of maximum weight. The quantitative approach to comparing repair options is successfully achieved, with no caveats.

6. Design and build a maintenance decision-making tool that incorporates the research theoretical methods, to be used in daily operations once implemented

The research culminates in Chapter 5 with the development of a prototype decision-making tool called Airmedt (**Air**craft **M**aintenance **E**valuation and **D**ecision **T**ool). The development of the tool involved a direct collaboration with the employees at a MRO maintenance shop. Their preferences and the Decision Support Systems framework requirements were analysed to determine how Airmedt should be designed, constructed, and implemented. The architecture of Airmedt has been designed such that it can be modified and expanded to add more functionality such as new types of users, structures, or analysis. The tool is constructed using license-free programming languages such as HTML and JavaScript. The current architecture is implemented as a standalone application, accessible through any device such as laptop, tablet, or smartphone. Airmedt has been demonstrated to the MRO and external industries (Transport for NSW) that showed interest in the tool and the straightforward nature of the interactive user-interface. The processing times are fast (<10secs), providing a detailed but clear break-down of repair option analysis. Therefore the objective to develop a maintenance decision-making tool has been successfully achieved, while future implementation is discussed in Section 6.3.

6.2. RESEARCH NOVELTY AND CONTRIBUTION

This dissertation contributes to the advancement of maintenance processes for composite aircraft. The research methodology is setup to address the gap in structural damage data and repair decision-making for composite aircraft. To the best of the author's

knowledge, there are no works specifically addressing the lack of composite damage data and how that may affect maintenance processes in daily operations.

The novelty of the research lies in using metal data to quantitatively predict the differences in impact risk between metal and composite aircraft. The dominant type of damage instance on previous generation of aircraft fuselage are related to impact (>50%). The metal aircraft of previous generations have spent substantial time in operations (>20 years), and so they have sufficient damage data to be analysed for the likelihood and repair consequence of an impact event. This research proposed and demonstrated that there are still lessons to be learnt for composites from metal damage data, specifically risk of impact. By assuming that the operations of the two aircraft types will remain comparable, similar impact threat experienced historically by a metal aircraft can be expected on its composite successor. Hence, the exact threat and likelihood is transferable to the composite data, but the risk will be different because the damage, and by extension the repair consequence, are different. The direct comparison of metal and composite aircraft impact risk demonstrate the threats they are most prone to. Thereby, maintainers can be made aware of the likelihood a damage will occur on composite aircraft and the type of repair action they must take as a consequence.

However, deciding on the repair action poses its own challenge due to numerous operational constraints and conflicting decision criteria. Hence, a novel approach to decision-making is developed that combines two different methods of Boolean Decision Tree (BDT) and Weighted Sum Method (WSM) to address option identification and option evaluation respectively. These two established methods have been adapted and expanded upon for use in maintenance Multi-Criteria Decision-Making (MCDM). Specifically, from an application perspective BDT helps to organise recurring constraints that influence the set of repair options that are feasible. Moreover, from a methodological perspective the WSM has been expanded through a global weight search algorithm that automates the evaluation process for all combinations of criteria weights. Thereby, the decision-maker has complete overview on which options perform best with respect to the criteria.

A decision-maker can gain insight from the decision-making model using Airmedt. The contribution of this tool is not only to demonstrate the application of the research but also to set the stage for formalising repair decision-making in an organisation. As such, the architecture has been designed and constructed such that it is easily expandable to all structures of the aircraft. The user-interface has been demonstrated to industry experts, ensuring that it is intuitive to use and accessible on any device. The user only needs basic computer skills and an understanding of maintenance operations to use Airmedt.

6.3. LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The radical notion of depending on metal damage data to inform composite damage repair decision-making is sure to raise questions on the assumptions taken and the limitations they pose. However, these limitations offer potential avenues for further development and research.

6.3.1. ESTIMATING DAMAGE AND IMPACT RISK

The process of estimating the impactors from metal damage is inherently a simplified depiction of an impact event. Assumptions for impactors are made such as being a spherical impactor, impact in the centre of a plate, and the flatness of the plate. In reality an impactor is rarely perfectly spherical or has isotropic properties. Since metal is the most recurring type of impactor material, such an assumption was a reasonable first step. However, other materials such as rubber, plastics, hail, and wildlife also pose a impact risk to the aircraft structure. Furthermore, impact can occur closer to or even on the frames and stringers of the aircraft fuselage. The interaction between support structures and the aircraft skin can lead to variation in impact response and resulting damage. These variations are further complicated by single or double-curved skin since curvature can cause a different plate response. Hence, addressing the other impactor material, off-centre impact, support structures, and plate curvature can expand the risk analysis to a broader set of risks.

An element of risk is consequence of impact, which has been simplified to direct repair cost because it allows for a straight-forward comparison between metal and composite plates. However, such deterministic fixed values of repair cost does not convey the full picture, because there may be other consequences to consider. MRO organisations may be interested in knowing the consequence of impact in terms of additional labour required, or disturbance to planned maintenance, or flight schedule. Such different forms of consequence quantification can provide additional layers of analysis to the MRO, enabling them to create appropriate mitigation plans.

The proposal of depending on metal data began with the assertion that composite damage data is limited, due to the short operational life. However, metal damage data also has its own limitations in data quality. Despite the size of the dataset the conversion process was impeded by the missing damage dimension description in a large portion of the damage instances, nearly 75%. Therefore, the best that could be done was to use the remaining dataset as a sample to demonstrate the process. This lack of descriptive quality highlights the issue of data completeness and how critical it is to be thorough in the knowledge capture. Although 110 out 120 sample data was successfully used to deduce the impactors, without the other damage dimensions, the best compromise is to extrapolate the findings to the other instances based on the recorded repair consequence.

6.3.2. MAINTENANCE DECISION-MAKING

Maintenance decision-making tackled both option identification and evaluation aspects of the process, each with potential for more development. Option identification as currently implemented in the decision-making model formalises the decision constraints to a single maintenance scenario. However, in the dynamic industry of maintenance and airline operations, conditions can change suddenly and dramatically. These changes can either introduce new constraints that a decision-maker must consider or constraints can be removed, allowing for more feasible options. Hence, there may be benefits to developing a dynamic Boolean scenario tree that identifies a scenario as it is currently implemented but also can identify a worst-case scenario and best-case scenario. In the event that conditions do suddenly change, the decision-maker is already prepped for the worst-case or best-case and can quickly adapt to the situation.

As for the maintenance evaluation the strength of WSM is also its weakness. The WSM uses a normalised scale where the ratings benchmark the options against each other. As a result, the worst option gets a rating of 0 but the best option gets 1. The advantage of this normalisation and scaling system is that the differences between the options become clear and helps the user to be more decisive. However, the disadvantage is that in some cases the difference is over-exaggerated. Take the 0 and 1 rated option as an example, where the ratings are with respect to cost and the option with rating 1 is the cheapest. If the decision-maker only considered cost as a priority and only looked at the cost rating, in an extreme case they may be selecting the cheapest option to save few cents while ignoring the other criteria where the more expensive option may have excelled. For now this disadvantage is compromised by also providing a detailed breakdown of the criteria evaluations. However, implementing a minimum absolute difference check between options is advised, and will require experimentation to establish where that threshold lies.

Emphasis was placed on making the decision-making model useful in daily operations, and considering only the most recurring decision criteria. This led to the use of the three criteria: cost, survivability, and downtime. In principle the methodology will remain the same if more criteria are considered. However, depicting the results of the global weight search algorithm will be increasingly complex. For example, the three criteria resulted in a global weight search depicted as a 2-dimensional triangular plane. If four criteria are considered then the global weight search results would form a 3-dimensional volume. Taking the concept further with more than four criteria would lead to global weight search results that are hypercubes in higher dimensions that humans cannot easily grasp or visualise. While, difficult to comprehend and implement, these higher dimensional criteria analysis would offer a challenging mathematical exercise.

6.3.3. AIRMEDT DECISION-MAKING TOOL

The most important next step for Airmedt is integrating it with relevant information systems to explore automating the tool. The standalone nature of the tool allowed for flexibility in development and experimentation with the functionality. However, the true test of the tool will be leveraging the knowledge from the dataservers of relevant stakeholders and departments. The automation will simplify the use case of the tool, reducing user inputs and the time necessary to set up the maintenance scenario for analysis. The integration should be carried-out in phases with one stakeholder at a time, starting with the maintenance shop. The different phases will help to identify the infant teething issues with the tool implementation, but more significantly ensure that the main requirements of the stakeholders are satisfied. The maintenance shop already provides the advise on the best repair action to take, and therefore running Airmedt simultaneously with other decisions will allow for the system validation.

Additionally, the tool can play an important role in the strategic planning of maintenance. Once Airmedt is implemented, all the decision history made through the tool can be collected over an extended period (e.g. 1-2 years). This decision history can be analysed by relevant management teams to improve the overall maintenance strategy. For example, a pattern of different stakeholder preferences can be identified and ratio-

nalised for future decisions. Perhaps, a recurring problem with a particular structure in the fleet is identified, motivating a need for purchasing an in-house spare in anticipation of future issues. There may be other insights gained by having an overview on a collection of daily decisions, benefiting the long-term operations and maintenance of the fleet.

A

DERIVED EQUATIONS FOR IMPACT MODELLING

Modelling Impact Damage on Aircraft Structure (MIDAS) has two variants: -M for metals, and -C for composites [1]. The derived equations used in MIDAS are stated in this appendix.

A.1. MIDAS-M

This section summarises the equations used in MIDAS-M and are separated into loading and unloading phases of impact. Chapter 2 mentions that MIDAS-M combines the local, transition and global deformation modes of a plate deflection. These deformation modes along with the novel transition region obtained from the weighted average of the penetration limit and conventional global plate bending are addressed. Next, the unloading phase determines the residual deformations using the strain profiles formed during the impact event.

A.1.1. LOADING PHASE

The impact force F_c given by Equation A.1, shows the vertical equilibrium of a clamped circular plate (radius of R_0), deformed by a spherical indentor (radius of R_i), and pure tensile membrane stress (σ_{rr}) [2, 3].

$$\begin{aligned} F_c = \quad & 2\pi r\, t\sigma_{rr} \sin\psi(r) && \text{with} \quad && \sigma_{rr(r)} = C_0\varepsilon_{rr}^n \\ & && && \varepsilon_{rr} = \tfrac{1}{2}\sin^2\psi \\ & && && t_0 = t\cos\psi_{(r)} \\ = \quad & 2\pi r C_0 t_0 \left[\tfrac{1}{2}\sin^2\psi_{(r)}\right]^n \cos\psi_{(r)}\ \sin\psi_{(r)}, \quad r \in (R_c, R_0) \end{aligned} \tag{A.1}$$

Where, $\psi_{(r)}$ is deflection angle of the plate as function of distance (r) from impact, C_0 is strength coefficient, n is work hardening exponent, ε_{rr} is radial strain.

Deflection angle of the plate is a function of the angle at point of contact:

$$\frac{r}{R_i} = \frac{\left[\frac{1}{2}\sin^2\psi_c\right]^n \cos\psi_c \ \sin^2\psi_c}{\left[\frac{1}{2}\sin^2\psi_r\right]^n \cos\psi_r \ \sin\psi_r} \qquad \text{with} \quad \cos\psi_c = 1 - \frac{\alpha}{R_i} \tag{A.2}$$

Displacement of the plate:

$$\delta = \alpha + \int_{R_c}^{R_0} \sin\psi_r(r,\alpha)\,dr \tag{A.3}$$

Penetration limit ($\psi_{c,f}$) following the peak of force-displacement curve [4]:

$$\cos\psi_{c,f} = \sqrt{\frac{1}{3+2n}} \tag{A.4}$$

Energy and force equations in terms of deflection of the structure:

$$E_b + E_m = \int_0^{w_s} F_b + F_m \, d\,w_s = \frac{1}{2}K_b {w_s}^2 + \frac{1}{4}K_m {w_s}^4. \tag{A.5}$$

$$F_b + F_m = K_b w_s + K_m {w_s}^3, \tag{A.6}$$

Where b is the bending contribution, m is the membrane contribution, w_s is the deflection of the structure, K is the stiffness factor.

Bending stiffness of a simply supported (SS) circular plate (CP) converted for flat plates using plate deflection theory (PT) [5, 6]:

$$w_{s,SS(x,y)} = \frac{4F_c}{ab}\sum_m\sum_n \frac{\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b}}{D\left[\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2\right]^2} \tag{A.7}$$

$$K_{b,SS}^{PT} = \frac{F_c}{w_{s,SS}(x=\frac{a}{2}, y=\frac{b}{2})} \tag{A.8}$$

Where a is the plate width, b is the plate length, F is the applied force, D is the bending rigidity. The bending stiffness of a clamped square plate and global deflection shape:

$$K_{b,CC} = K_{b,CC}^{CP}\left(\frac{K_{b,SS}^{PT}}{K_{b,SS}^{CP}}\right) \tag{A.9}$$

$$w_{s,CC(x,y)} = \frac{F\,K_{b,CC}}{4}\left(1-\cos\frac{2\pi x}{a}\right)\left(1-\cos\frac{2\pi y}{b}\right) \tag{A.10}$$

Where, the bending stiffness of a circular plate that is clamped (CC) and simply supported (SS) is determined with the Young's modulus E_r and Poisson ratio ν_r [7]:

$$K_{b,CC}^{CP} = \frac{4\pi E_r t^3}{3(1-\nu_r^2)R_0^2} \tag{A.11}$$

$$K_{b,SS}^{CP} = \frac{4\pi E_r t^3}{3(3+\nu_r)(1-\nu_r)R_0^2} \tag{A.12}$$

Transition region shape is obtained with a weighted average applied to the local and global deflection limit cases ($\psi_{m(r)}$ and $\psi_{b(r)}$). The transition point R_t is where the deflection angles $\psi_{m(r)} = \psi_{b(r)}$, and the event's deflection angle is $\psi_{e(r)}$.

$$\psi_{e(r)} = \psi_{b(r)} \frac{F_m}{F_c} + \psi_{m(r)} \frac{F_b}{F_c} \tag{A.13}$$

The contact energy leading to the relative displacement (Δw) of impactor with respect to the bending deflection:

$$E_c = \int_0^{\Delta w} F_c \, d\Delta w \qquad \text{with} \quad \Delta w = \delta - w_{s(r=0)}. \tag{A.14}$$

A.1.2. UNLOADING PHASE

The unloading phase ends with a final residual dent left behind due the different contributions of the strain distributions:

$$\varepsilon_{(r)} = \varepsilon_{m(r)} + \varepsilon_{b(r)} \tag{A.15a}$$

$$\varepsilon_{m(r)} = \frac{1}{2} \sin\left(\frac{dw}{dr}\right)^2 \tag{A.15b}$$

$$\varepsilon_{b(r)} = -z \frac{d^2 w}{d^2 r} \tag{A.15c}$$

The final deflection of the plate:

$$w_{p(r)} = \begin{cases} w_{e(r)} - (R_p - r)\tan\left(\psi_{e(r)}\right) & \text{for } R_c < r < R_p \quad \text{(A.16a)} \\ w_{p\,(R_c)} + R^* - \sqrt{R^{*2} - r^2} & \text{for } r < R_c \quad \text{(A.16b)} \end{cases}$$

The relaxed impactor radius:

$$R^* = \frac{R_c}{\sin \psi_{p(R_p)}}. \tag{A.17}$$

A.2. MIDAS-C

Next MIDAS-C equations are summarised, also separated into loading and unloading phases of impact. Chapter 3 indicated that MIDAS-C depicts composites deformation into two regions local indentation and global plate deflection. The unloading phase determines the permanent indentation resulting from the indentor and using the final effective stiffness calculates the residual deflection of the plate.

A

A.2.1. LOADING PHASE

Composite alternate for bending stiffness of simply supported flat square plates can be obtained from plate deflection theory [5, 6] where a, b, F and D being respectively the plate width, length, applied force and the bending rigidity.

$$w_{s,SS(x,y)} = \frac{4F_c}{ab}\sum_m\sum_n \frac{\sin\left(\frac{m\pi x_0}{a}\right)\sin\left(\frac{n\pi y_0}{b}\right) sin\left(\frac{m\pi x}{a}\right) sin\left(\frac{n\pi y}{a}\right)}{D_{11}\left(\frac{m\pi}{a}\right)^4 + 2(D_{12}+2D_{66})\frac{m^2n^2\pi^4}{a^2b^2} + D_{22}\left(\frac{n\pi}{b}\right)^4} \tag{A.18}$$

$$K_{b,SS}^{PT} = \frac{F_c}{w_c} \tag{A.19}$$

Bending stiffness for clamped square plates ($K_{b,CC}$) is adjusted using Equation A.9. The elastic contact pressure is proportional to the deflection profile $\delta_{\alpha(r)}$:

$$\delta_{\alpha(r)} = \alpha - R_i\left[1 - \sqrt{1\left(\frac{r}{R_i}\right)^2}\right] \tag{A.20}$$

$$p_{(r)} = K_e\delta_{\alpha(r)} \tag{A.21}$$

Indentation larger than the elastic limit (α_{e-0}), the elastic contact pressure distribution exceeds the compressive contact strength (Z_c), leading to a plastic region of radius (R_p). The contact force and energy as a function of indent depth:

$$F_c = \begin{cases} 2\pi K_e\int_0^{R_c} p_{(r)}rdr, & \text{if } x<0, \text{ with } a_{e-0}=\frac{Z_c}{K_e} \\ \pi R_p^2 Z_c + 2\pi K_e\int_{R_p}^{R_c} p_{(r)}rdr, & \text{if } x\geq 0, \text{ with } K_e=\frac{E_t^*}{E_t}. \end{cases} \tag{A.22}$$

$$E_c = \int_0^{\alpha} F_c d\alpha \tag{A.23}$$

The effective transverse modulus (E_t^*) is dependent on the relative rigidity of the impactor, where the target is represented by E_z [8], impactor stiffness E_1 and Poisson ratio ν_1 [6, 9, 10]:

$$\frac{1}{E_t^*} = \frac{1-\nu_1}{E_1} + \frac{1}{E_z} \tag{A.24}$$

A modelling approach that modifies the bending contribution, where F_{d1} refers to the DTL, the initiation of delamination at a single delamination interface [11].

$$F = \begin{cases} K_b w_s + K_m w_s^3, & \text{if } K_b w_s < F_{d1} \\ F_{dn} + K_m w_s^3, & \text{if } K_b w_s \geq F_{d1} \end{cases} \tag{A.25}$$

An estimate of n^* equivalent circular delaminations:

$$n^* = \bar{A}\left[\bar{A}_{45^\circ} n_{\Delta 45^\circ} + n_{\Delta 90^\circ}\right] \tag{A.26}$$

The estimate for n^* depends on the number of interfaces ($n_{\Delta\theta}$) with a specific ply mismatch angle (i.e. $\Delta\theta = 45°$ or $\Delta\theta = 90°$) [12, 13]. Morita *et al.* [14] proposes a non-dimensionalised coefficient for bending mismatch (β) [13], where ΔQ_{11} is the in-plane stiffness mismatch and D_{11} is the entire laminate bending stiffness, and β is based on the radial average over each interface:

$$\beta_i = \frac{1}{2\pi}\int_0^{2\pi} \frac{\Delta Q_{11(\theta)} z_i}{D_{11(\theta)}} d\theta \tag{A.27}$$

Using reference at the largest in-plane difference of laminate, $\beta_{i,\max}$, Equation A.26 is modified into Equation A.29.

$$\beta_{i,\max} = \frac{1}{2\pi}\int_0^{2\pi} \frac{|Q_{11(0°+\theta)} - Q_{11(90°+\theta)}| z_i}{D_{11(\theta)}} d\theta \tag{A.28}$$

$$n^* = \bar{A}\sum_{i=1}^{n} \frac{\beta_i}{\beta_{i,\max}} \tag{A.29}$$

Initial Fibre Breakage (IFB) leading to the vertical equilibrium at the contact edge is estimated by Equation A.30a [15], where σ_0 is uniform membrane stress, ε_0 is the membrane strains, E_r is the radially averaged Young's modulus, and Poisson's ratio υ_r. The vertical equilibrium simplifies to the membrane failure criterion Equation A.30c [15]:

$$F_{IFB} = 2\pi t R_c \sigma_0 \sin\psi_c \tag{A.30a}$$

$$= 2\pi t R_i \sin\psi_c \varepsilon_0 \frac{E_r}{1-\upsilon_r} \sin\psi_c \tag{A.30b}$$

$$= 4\pi t R_i \varepsilon_0^2 \frac{E_r}{1-\upsilon_r} \tag{A.30c}$$

To determine the penetration point requires the determination of minimum number of ineffective plies n_t as shown by the inequality in Equation A.31. The corresponding maximum plate deflection ($w_{IFB,nt}$) is given by Equation A.32.

$$F_{IFB,nt} < F_{IFB} - F_{dn} \tag{A.31}$$

$$w_{IFB,nt} = \sqrt[3]{\frac{F_{IFB} - F_{dn}}{K^*_{m(n_t)}}} \tag{A.32}$$

A.2.2. UNLOADING PHASE

Permanent indentation (α_0) remains after exceeding a critical indentation (α_{cr}) [16]. The relation Equation A.33 is based on the load path during unloading Equation A.34.

$$\frac{\alpha_0}{\alpha_{me}} = l - \left(\frac{\alpha_{cr}}{\alpha_{me}}\right)^{\frac{1}{q}} \tag{A.33}$$

$$\frac{F}{F_{me}} = \left(\frac{\alpha - \alpha_0}{\alpha_{me} - \alpha_0}\right)^q \tag{A.34}$$

A

This path is depends on the force (F_{me}) and indentation (α_{me}) at the end of loading phase. The unloading coefficient q is based on experimental data, but $q = 2.5$ is a conservative approximation[16].

The bending and membrane stiffness terms are adjusted in the unloading phase with the final effective stiffness K_m^*, which is assumed equal to be the unloading stiffness K_m^u. The unloading bending stiffness K_b^u is given by:

$$K_b^u = K_b \frac{w_{DTL}}{w_{me}} + K_b^{DTL}\left(1 - \frac{w_{DTL}}{w_{me}}\right) \qquad \text{with } K_b^{DTL} = K_b \frac{w_{DTL}}{w_{me}} \tag{A.35a}$$

$$= K_b \frac{w_{DTL}}{w_{me}}\left(2 - \frac{w_{DTL}}{w_{me}}\right) \tag{A.35b}$$

which effectively averages the stiffness contributions before and after delamination. The resulting unloading relation for deflection:

$$F = F_{me} - (K_b^u w_u + K_m^u w_u^3) \quad \text{with } w_u = w_{me} - w \tag{A.36}$$

The residual deflection is obtained by setting Equation A.36 equal to zero.

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B

DAMAGE FREQUENCY AND SURVIVABILITY

One of the main metrics being used to evaluate repair decisions is inherent structural survivability. In order to quantify and forecast the survivability degradation, Poisson processes are implemented into the overall decision support model.

B.1. NON-HOMOGENEOUS POISSON PROCESS (NHPP)

Non-Homogeneous Poisson Process (NHPP) is a Poisson process characterised by a non-constant intensity function $\lambda(t)$, satisfying the following three conditions:

1. $N = 0$
2. For any $a < b, N(a,b]$ $POI\left(\int_a^b \lambda(t)dt\right)$
3. The process has the independent increments property, i.e., for any non-overlapping intervals $(t, t+\Delta t), (s, s+\Delta s)$, $\Delta N_{(t,t+\Delta t)}$ and $\Delta N_{(s,s+\Delta s)}$ are independent

Where,
$\lambda(t)$ is intensity function
t, s is time or flight cycles
N is the number of failures in an interval

Equation B.1 gives a particular form of the intensity function, known as the power law process or the Weibull intensity function.

$$\lambda(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1} \tag{B.1}$$

Where,
β is the Weibull shape parameter

θ is the Weibull scale parameter

The Weibull intensity function is flexible in its ability to demonstrate various skews and spreads in the data with the shape and scale parameter. This flexibility allows the NHPP to represent structural life models for a wide variety of components. NHPP also adopts an as-bad-as-old repair philosophy, which means that any repair done assumes that the survivability of structure has not been changed and will not improve the lifetime. Rather as-bad-as-old type repairs only corrects the current fault so that it continues to function but also the survival probability continues to degrade at after the repair. NHPP can assume to be an independently and identically distributed (iid) model, and in fact homogeneous Poisson process (HPP) is just a special case of NHPP where the intensity function happens to be constant. Probability of failure occurrence is characterised by Equation B.2.

$$P(N) = \frac{e^{t\lambda(t)}\big(t\lambda(t)\big)^N}{N!} \tag{B.2}$$

B.2. RENEWAL PROCESS (RP)

Renewal Process is an as-good-as-new repair process, where the intensity function is also assumed to be non-constant. RP is preferred over HPP because of its ability to illustrate deteriorating and improving systems. Once again the Weibull distribution is used to characterise the process. First the expected and variance of time-to-failure must be calculated as shown by Equation B.3.

$$\eta = \theta\Gamma\left(1+\frac{1}{\beta}\right), \tag{B.3a}$$

$$\sigma^2 = \theta^2\left[\Gamma\left(1+\frac{2}{\beta}\right) - \left(\Gamma\left(1+\frac{1}{\beta}\right)\right)^2\right] \tag{B.3b}$$

Where,
η is the expected time or flight cycles to failure
σ^2 is the variance of time or flight cycles to failure
Γ is the gamma operator

To calculate the probability of failure occurrence using the renewal process is shown by Equation B.4.

$$\lim_{t\to\infty} P\big(N(t) < a(t)\big) = \Phi(y), \tag{B.4a}$$

$$a(t) = \frac{t}{\eta} + y\sigma\sqrt{\frac{t}{\eta^3}} \tag{B.4b}$$

Where,
Φ is the cumulative distribution function of Normal
a is the expected failures in an interval
y is the Normal distribution test value for probability of failure
t is the time or flight cycles, since as-good-as-new state

B.3. SEQUENTIAL MAINTENANCE EVENTS SURVIVABILITY

The cumulative distribution functions of Poisson processes are detailed but they are valid for only one type of repair event. There are maintenance options that are characterised by multiple types of repair events. In such cases, sequential event survivability needs to be calculated.

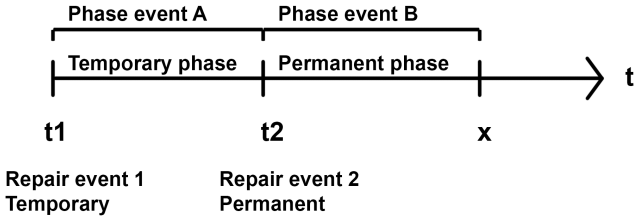

Figure B.1: Multiple repair event maintenance scenario

Take for example a maintenance scenario shown in Figure B.1. A damage is found and undergoes the first repair event at t_1, a temporary repair which is assumed to be minimal repair and hence follows NHPP during the temporary phase. A certain amount of time later the temporary repair is followed up with a permanent repair at t_2. The second repair event renews the structure to as-good-as-new, and the survivability past t_2 is demonstrated by renewal process for the permanent phase.

Let's denote temporary phase and permanent phase as phase event A and phase event B respectively. Phase event A is for the time interval of $t_1 < t < t_2$, whereas phase event B is for $t > t_2$. These two phase events are assumed to be independent, meaning that the survivability in phase A does not affect phase B survivability. In this scenario $P(A)$ is the survivability of during phase A which is simply Equation B.2 from NHPP for $t = t_2$. Then let's explore the probability of surviving till $t = x$, which means surviving both phase events. The probability of surviving just phase event B, $P(B)$ is given by Equation B.5 following the renewal process where $N(t)$ is actually $N(x–t2)$ because a new process has begun with repair event 2 at t_2. Now that $P(A)$ and $P(B)$ have been established, the probability of surviving two independent phase events is given by conventional statistical methods where:

$$P(A \cap B) = P(A)P(B) \tag{B.5}$$

Equation B.5 is what is referred to as sequential event survivability. Using this equation, the probability of surviving multiple sequence of independent repair events and phases can be quantified.

C

FUTURE STAKEHOLDER REQUIREMENTS FOR AIRMEDT

The development of current version of Airmedt focused on the requirements set by the maintenance shop. However, future development will involve other stakeholders in the decision-making process: Maintenance Control Centre (MCC), Operational Control Centre (OCC), and external vendors. Each of these stakeholders have their own uniqure requirements for Airmedt functionality.

Maintenance Control Centre (Management): The MCC is in charge of the maintenance scheduling for the fleet of aircraft. MCC is the final decision-maker choosing the option, although in practice it is a collaborative process making sure a consensus among stakeholders is reached.

Requirements for future version of tool

- Able to receive damage report and the related repair options from maintenance shop
- Able to review the options with respect to overall maintenance planning
- Ability to consult with other parties to ensure the details are correct and not conflicting
- Send final decision on repairs
- Update the overall maintenance planning if needed
- Receive confirmation on repair execution from maintenance shop

Operational Control Centre (Intermediary): The OCC is essentially the customer of MCC and maintenance shop. They are in-charge of operating the fleet of aircraft in their network

Requirements for future version of tool

- Able to receive damage report and the related repair options from maintenance shop
- Able to review the options with respect to overall fleet operations planning
- Ability to consult with other parties to ensure the details are correct and not conflicting
- Send confirmation of preferred option
- Update the overall fleet operations planning if needed
- Receive confirmation on repair execution from maintenance shop

External vendors (Intermediary): While the maintenance shop is in charge of stocking, some parts require too much capital to be stocked. Therefore, external vendors act as suppliers providing services when asked but are not involved in making the final decision.

Requirements for future version of tool

- Able to receive resource estimates request from maintenance shop
- Able to review their stock and availability
- Ability to send the estimates to the maintenance shop
- Receive confirmation on services or products required
- Update the stock or availability of services

CURRICULUM VITÆ

Venkata Sai Viswanath DHANISETTY

V. S. Viswanath Dhanisetty was born on August 31st, 1990 in Nellore, India, and since then has lived and studied in seven different countries. He completed high-school following the International Baccalaureate (IB) curriculum in Munich International School in 2008. Afterwards he moved to Delft to pursue a Bachelor of Science degree in the faculty of Aerospace Engineering at Delft University of Technology (TU Delft). Apart from the core subjects of the Bachelor programme, Mr Dhanisetty followed a 6-month minor in Project Management at the faculty of Technology, Policy, and Management (TPM). He completed the Bachelor programme in 2011 with the Design Synthesis Exercise (DSE) project on 'Dutch airport of the future,' conducted over a period of 10 weeks with a group of 10 students.

Mr Dhanisetty started the Master of Science programme at the Department of Air Transport and Operations (ATO) in 2011. During the programme, he interned at Belle Air Albania covering the topic of fleet management and its effects on the airline's operational and maintenance cost. His collaborations with industry continued with the thesis research on maintenance interval optimisation for cross-industrial application: facilitated by World Class Maintenance (WCM), internships at Cargill (agriculture and food processing), RET (public transport), and Jetsupport (aircraft maintenance). Mr Dhanisetty completed the programme and graduated with a Master of Science degree in 2014.

In April 2015 Mr Dhanisetty began his position as a PhD Candidate at ATO, funded by KLM E&M. The PhD research focused on maintenance processes for composite structures. The work has been presented in local and international platforms, leading to several publications. Alongside the research, he has undertaken educational tasks to supervise Bachelor and Master students: one 2nd-year Bachelor project, two DSE projects, three Master thesis projects. Additionally, Mr Dhanisetty has been a member of the PhD Council representing the departments of Aircraft Noise and Climate Effects (ANCE), and ATO. The Council is tasked with organising social and academic events for the PhD candidates of the Aerospace Engineering faculty, and fostering communication between the candidates and the Graduate School. In April 2019, Mr Dhanisetty commenced his role as a lecturer for 'Airport of the Future,' a minor in the Bachelor programme.

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