CRANFIELD UNIVERSITY

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Optimise Repair Strategy Selection and Repair Knowledge sharing to Support Aero Engine Design

School of Aerospace, Transport and Manufacturing

PhD
Academic Year: 2014 - 2015

Supervisors: Dr Yuchun Xu
Professor Andrew Starr

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This thesis is submitted in partial fulfilment of the requirements for the degree of PhD

ABSTRACT

Recent growth in aviation industry, large civil jet engines OEMs (Original Equipment Manufacturer) and MROs ((Maintenance, Repair and overhaul)) have emphasised on decreased profits, poor technology selections and maintenance focused design. This has generated service based approach in their selling, offering all customers' requirements, known as servitisation. The servitisation has increased profits but did not solve the challenges of poor technology selection and design. The difficulties involved within servitisation entails rationalised decision making often with high risk and very limited information.

This thesis assesses the most suitable Multi-criteria decision making (MCDM) in concurrence with OEMs and MRO focus groups that recognises the industrial requirements and proposed a novel selection method which is an AHP algorithm based on MCDM in efforts to address business KPIs in aero engine servitisation. This AHP algorithm based MCDM develops an optimised repair process/technology selection framework which is called ORSS (Optimised Repair Selection Strategy). The ORSS applies the business KPIs (Quality Cost Delivery) as a selection criteria combined with the repair engineer's requirements and expert's evaluation of processes/technologies based on a component and its damage-mode to provide the optimised repair process/technology selection that also compliments the components lifecycle repair strategy. A structured knowledge sharing framework has also been developed. This consists of the information that the designers can update to help repair teams to become more effective and efficient in repair and services critical information tasks.

These frameworks were validated successfully by experts within the design, repair and service teams at Rolls Royce. These frameworks have shown high levels of improvements in repair process selection and the key knowledge sharing for designs.

Keywords: repair process, gas turbine components, optimisation, Hybrid AHP, Aero-engine components repair, Knowledge feedback.

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LIST OF ABBREVIATIONS

Bn	Billion
IT	Information Technology
KPI	Key performance Indicators
LCC	Life Cycle Cost
MRO	Maintenance Repair and Overhaul
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making
OE	Optimised Repair Selection Strategy
OEM	Original Equipment
ORSS	Original Equipment Manufacture
Plc.	Public limited company
QCD	Quality Cost and Delivery
R&D	Research and Development
RR	Rolls Royce

CMM	Coordinate Measuring Machine
CNC	Computerised Numerical Controlled
EBW	Electron Beam Welding
FOD	Foreign Object damage
GOM	Gesellschaft für Optische Messtechnik
GV	Guide Vanes
H/T	Heat Treatment
HCF	High cycle Fatigue
HVOF	High Velocity Oxygen Fuel
LCF	Low cycle Fatigue
MEK	Methyl Ethyl Ketone (butanone)
NC	Numerically controlled
NGV	Nozzle Guide Vanes

Chapter 1

1 Introduction

The growth of the aviation industry has made the business competitive, which not only include the business aspect but the technical aspects also. The organisation getting affected by this are mainly OEMs and MROs. The MRO activities account for around 50% of the revenues within the aviation sector. Optimisation in these activities will make a considerable impact in competiveness of OEMs and MROs. There is a strong need of optimised selection of process which addresses business KPIs which are often overlooked. The research is indicating the key KPIs are quality cost and delivery, as these the prime concerns for all aviation industry, how the best compromise can be achieved is the main theme of this research. This research address the process selection in repair and repair knowledge sharing with aero engine designers for repair focus design. It also compliments the repair strategy through-life of aero engine components.

1.1 Research Motivations

The passengers are increasing and it will reach over 30% by 2017 compared to 2012 (IATA Airline Industry Forecast 2013-2017). This has increased the market for new (low cost carriers) and renewed (investments in the existing airlines with mergers and code sharing) businesses which have made this market more competitive. This competition has started the contest to pursue for any impending for cost saving and competitiveness. The is also leading the industry to consider new technologies and their effects on operating cost, overall cost of ownership, quality and delivery of assets like aircraft and engines. The major part of life cycle cost (LCC) is consists of maintenance, repair and overhaul (MRO) of the aircrafts. The engine MRO is the largest expense for aircraft operators as given in the fig 1, according to research (Jet Engine, Consulting. 2010)

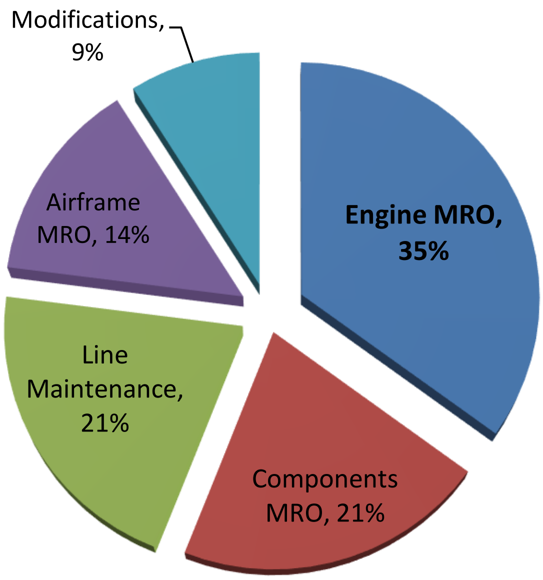


Figure 1: Aircraft MRO costs

The operating cost involved in large aircraft consist of airframe checks and line maintenance which are mandatory. Whereas components MRO includes non-airframe parts excluding engines. The modification are done to improve the efficiency and effectiveness of the aircraft. The engine MRO is one of the most important factor in aircraft up keeping which is also the most demanding in cost and quality.

In civil aviation, most large aircraft uses gas turbine engines commonly known as aero engines/ turbo fan engines. These engines are multifaceted which requires extensive skilled labour for MRO activities which includes disassembly, pre-inspections, repairs, post-inspections, reassembly, test and acquisitions. Due to high repair cost, required quality and delivery, the OEMs and engine operators consider engine MRO for their competitiveness.

Currently, the companies are focused to provide maintenance, repair and overhaul (MRO) for the entire life of their components, which ultimately acquires operating and maintaining the cost of equipment; enhance the components' availability, durability and reliability; and intensify asset value and customer desirability (Rolls Royce, 2012). However, the companies are not adequately equipped to provide the extent of services that customers may require. The new techniques and methods can be employed to enhance the efficiency and effectiveness of MROs, and to gain more revenues (Deloitte, R., 2012, and Visiongain, 2011). These new methods and techniques may include cost-benefit analysis, better decision making in alternative repair technology selection (i.e. Multi criteria decision making or analysis) and an improved repair knowledge model for designers.

The strict standards within the aerospace industry, highly skilled workforce, high operational cost and huge commitment of infrastructure for MROs activities are the potential threat to MRO business. To mitigate these challenges MROs require multi criteria decision analysis for repair selection techniques. These techniques may also help the MROs to be more competitive. It will provide the improved repair knowledge model for designers to facilitate efficient knowledge sharing within the Aero Engine.

Products' after sales service programs provided by OEMs increase customers' asset utilisation and ultimately effect on market capture by the OEM. To fulfil the customers need, the OEMs (e.g. aero gas turbine) have changed their business model from selling products to selling services (Tuppen and Williams, 2009). Therefore, it has become vital for companies to provide competitive products through its life.

1.1.1 Business Case

Three major manufacturers dominate the large commercial jet engine market. It can be seen from Figure 2 and Table 1 that aero engine companies have huge revenues and aggressive competition.

Table 1: Aero engine companies revenues

Company	2010 Revenues (millions)	2009 Revenues (millions)
Rolls Royce	£11,085	£10,414
GE Aviation	£11,287*	£11,998*
Pratt & Whitney	£8,286*	£7,939*

- *(See appendix for more details; Large Civil Aircraft Engines)*
- ** at an exchange rate of £1 = $1.5609*

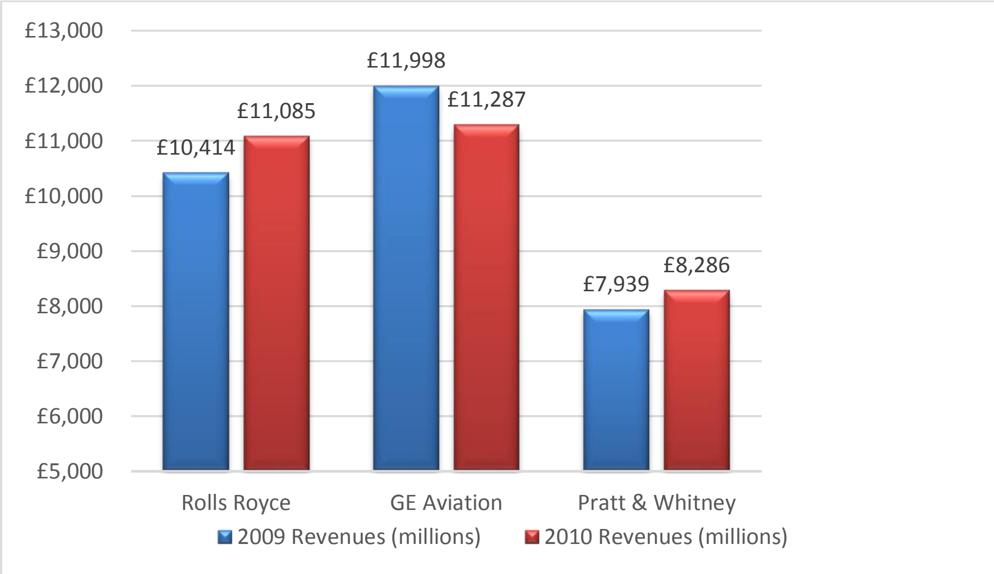


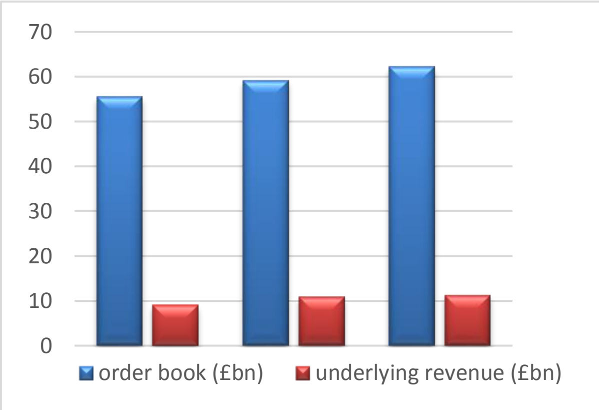
Figure 2: Aero engine companies revenues

The total revenues of OEMs consist of approximately 50% from MRO i.e. a big part of the revenues are contributed by repair and after sales services. The sponsor Rolls Royce is a leading OEM of civil and defence gas turbine engines and follows the same trend. Therefore, it is at the heart of Rolls Royce R&D to remain focused on MRO's future growth. It can be seen from Table 2 (Figure 3 and Figure 4) that the order book has increased significantly, which has a significant effect on service revenues.

Table 2: Revenues of Rolls Royce plc. (Yearly accounts)

Year	**Order book (£bn)**	**Underlying revenue (£bn)**	**Underlying profits (£m)**	**Service**	**OE***
2009	55.5	9.1	880	52%	48%
2010	59.15	10.86	955	49%	51%
2011	62.2	11.27	1157	53%	47%

**OE = Original Equipment*



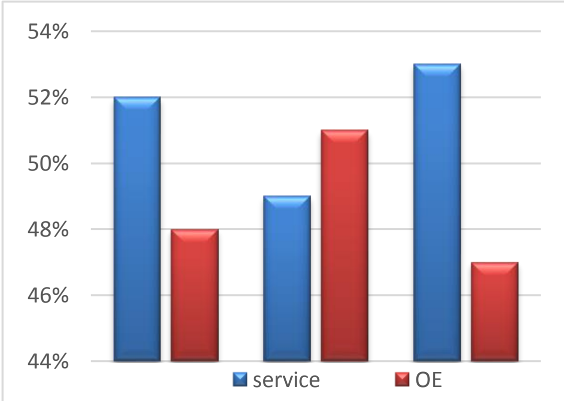


Figure 3: Order book Vs underlying revenues (Rolls Royce plc)

Figure 4: Service Vs OEM (Rolls Royce plc)

The growth of commercial aircraft MRO market from £50.2 bn in 2011 will become £86.4bn in 2021(Visiongain, 2000) (See Table 3, Figure 5 and Figure 6). If the assumptions are correct, there is a significant business opportunity to be captured.

The Rolls Royce's financial report states that the Rolls Royce's "groups underlying revenue in year 2011 have increased by four per cent to £11.3bn. This includes a nine per cent growth in services revenue to £6.0bn that is more than offset a one per cent reduction in OE revenue to £5.3bn. OE performance included strong 18 per cent growth in Civil Aerospace offset by a greater than anticipated reduction of 23 per cent in Marine OE revenue. Underlying services revenue continues to represent more than half (53 per cent) of the Group's revenue". Further, in "underlying profit before tax increased 21 percent to £1.16bn. This was due to a better mix between OE and services, an improvement in productivity resulting from the focus on cost"

Table 3: Forecast table for future for MRO market

Year	Total aircraft, commercial growth (£bn)	Rolls Royce Total underlying revenue (£bn)	Underlying profits (£bn)	Service	OE
2011	50.2	11.27	1.157	53%	47%
2016 (5.2%growth)	64.2	12*	1.200**	55**%	45%
2021 (6.0%growth)	86.4	15.55**	1.250**	55**%	45%

- **if the growth of whole sector meet the forecasted growth*
- ***according to assumptions. (Deloitte, R., 2012 and Visiongain, 2011).*

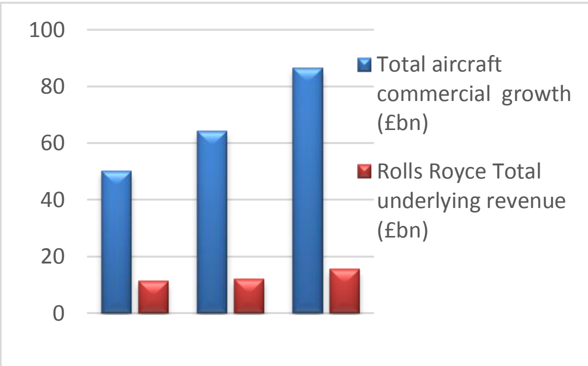


Figure 5: Commercial aircraft growth Vs revenues (Rolls Royce plc)

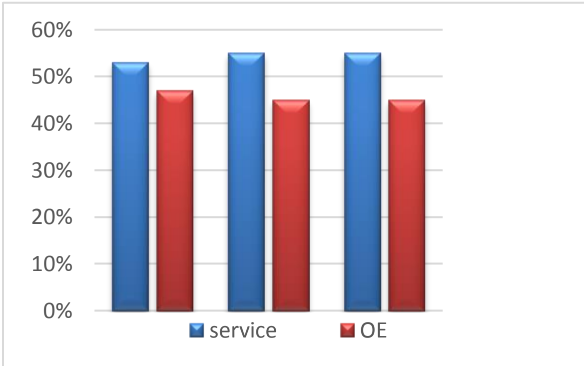


Figure 6: Service Vs Original equipment (Rolls Royce plc)

The trend of revenue contribution within the aero engine market has influenced the initiation of this project.

The other aspect is that (Birch N T 2000) future drivers for the civil engine will have to reduce the cost of ownership specifically the product unit cost and the maintenance cost with reliability. Birch also predicted that total sales of the engine will be around 83000 units over the next 20 year worth more than $350bn.

Therefore, it is paramount to have a robust repair strategy to exploit the growth in revenues. All these findings present many challenges and every challenge must address the associated opportunity with it; in this case of this project the repair selection process is also an opportunity for future cost and performance benefits.

Research Motivations

Optimised repair process selection strategy is a very important element of the aviation industry that has been neglected.

There are some other benefits and interests for RR that are worth mentioning for the scope of this project:

- Lower maintenance cost with improved asset reliability
- Effective repair for customer values & productivity improvement
- Culture – data driven, proactive, planned & scheduled repair fully integrated with operations and design – shared ownership
- Technology and design driven Repairs
- Manage the repair like managing the production and design
- Reparability is viewed as part of the culture, such as a safety

The effective repairable designs are also strong needs of the future design which is based on effective and efficient repairable design.

In an effort to make MRO business more effective, the steps to manage change in MRO business is vital. The challenge for the industry is to develop a repair process selection method which gives the cost benefit analysis before committing the repair. It is also important to address potential cost savings in repair process selection. The new process/technology introduction provides a step change in the performance rather than a continuous improvement in repair processes. The decision making in repair selection process does not utilise the multi criteria decision making techniques which other industries has successfully implemented. A bespoke repair cost model for Rolls Royce to optimised repair selection is not available.

The technical reports and MRO data suggest that there is a need to extract value from their repair process for the future hike in MRO business (Visiongain 2011). Hence the repair selection techniques are required by MROs to be more competitive.

Through-life Engineering Services is also increasingly important elements of service-based contracts for aero engines. The service element involves a considerable amount of repair/remanufacturing work for engine components. Rolls-Royce Repair Team is committed to identify optimise repair/remanufacturing processes and technologies, and feedback them to design engineers for supporting life cycle design of aero engine. Currently there is a need of an approach and a tool that can be used, to optimise repair strategy for aero engine damage. There is also a need of efficient and effective repair knowledge sharing at the early design stage.

1.2 Research Scope

The model will help to find an optimum technology process selection to OEMs and MRO.

The scope of the research is to provide the assistance in finding the optimised technology selection to the OEMs and MROs in their components repair.

In the product development phases, the developed system can be used for the estimation of repair costs in the design phase, explicitly in the conceptual and detailed design phases. The system can also be used to develop cost quotations.

The research focuses on successful completion of tasks relating to optimised selection of repair strategy and knowledge base model for efficiency in design aero engine. This research is focused on effective and efficient repair technology selection for aero engine components repair and sharing of repair knowledge among repair and design teams of aero engine components.

The research recommend future efficiencies to be capitalised from the MRO and future size of the aero engine repair market. RR is motivated towards such development to become more competitive in the aero engine repair market. It also suggests the efficiencies from manufacturing to repair, which are not only vital, but also holds a value chain for repair and waste saving for manufacturing.

The scope will be limited to developing a repair strategy that can analyse the repair strategy selection for the part coming from the manufacturing site failing QA or from a repair site offering repair.

The pathway to achieve the aim and objective of the research comprises of exploring the following four areas:

1. Need to explore and examine the capacities and capabilities for selection of different repair technologies. (e.g. cleaning, welding process in repair)
2. Repair technology selection based repair knowledge sharing with the designer, therefore an approach employing a tool to update the aero engine design team from input of repair knowledge.
3. Modelling is third area to explore and develop a specific model for capturing efficiencies in repair processes.
4. Repair technology selection requires multi criteria based decisions support this area needed to be explored where a scheme of intelligent and rational decision making can take place at give stage

1.3 Research Aim and Objectives

This research aims to develop a knowledge based approach to optimise the repair strategy (including technologies and processes) selection of aero engine repair, and to develop a repair knowledge model to support efficient and effective knowledge sharing at an early stage of aero engine design.

The context of this research is mainly focused on OEM/MRO business of large civil turbine/aero engine, components level optimisation in repair selection process Therefore, all the information and data collected address the challenges facing by the OEM.

The research Objectives and deliverables can be simplified as followings

- Identify limitations in different aerospace repair techniques/processes and knowledge feedback to designers
- What are the aerospace components repair process selection processes and how they can be optimised?
- What are the knowledge sharing mechanisms from repair to design and how it can be improved?

- Develop a simple and realistic model for selecting different types of repair techniques/process used in aerospace components
- Develop Multi-criteria decision making framework to select repair techniques/process based on performance criteria
- Develop knowledge sharing from repair to design
- Validate repair knowledge framework for designers

1.4 Contributions

The novelty and contributions of this research are outlined as:

- Optimised repair selection strategy framework
    - Implication of business KPIs in repair environment
    - KPIs as QCD and their implication on components repair
    - Expert based algorithms merged into KPIs to support optimised repair
    - Tool to evaluate the repair selection technology for components' repair
- Repair effectiveness and efficiency interpretation
    - Analysis of the repair efficiency (from repair to remanufacturing based on cost)
    - Analysis of repair effectiveness (from repair to remanufacturing based on design life of the components)
    - Component lifecycle repair strategy development
- Repair knowledge sharing framework
    - 7 key steps for knowledge sharing from repair to design
    - What and why of repair knowledge sharing with aero engine design teams
    - Key design updates based on repair knowledge sharing to supports 'Repair focus design'.

1.5 Publications

1.5.1 Journal

Khan, Atif., Xu, Yuchun and Starr, Andrew. (2015), "Optimised repair process selection strategy for aero engine Components", *CIRP Journal of Manufacturing Science and Technology,* special issue to be published in 2016 (Submitted)

Khan, Atif., Xu, Yuchun and Starr, Andrew "Expert based algorithms merged into to supporting repair cost modelling "Journal of Operations Management (under progress)

Khan, Atif., Xu, Yuchun and Starr, Andrew "Repair knowledge sharing framework for aero engine components" Journal of Knowledge Management (under progress)

Khan, Atif., Xu, Yuchun and Starr, Andrew "Repair Effectiveness and Efficiency in Mechanical Systems" European Journal of Operational Research, (under progress)

1.5.2 Conference

Khan, Atif., Xu, Yuchun and Starr, Andrew. , "Issues and challenges in aero engine components repair cost modelling. (Awaiting approval)

1.6 Thesis Layout

Organisation of the thesis is as follows:

Chapter 2 (Methodology) This chapter identifies the theoretical approach ideal for operational research and presents an appropriate research methodology to achieve the aim of this research. Lastly, how the research was designed to achieve the aims.

Chapter 3 (Literature Review) presents the critical overview of the aero engines (aircraft gas turbines engines), focused on large civil aero engines. Detailed literature review of maintenance and repair of aero engine, its repair processes, different damage-mode in aero engines components and knowledge sharing within aero engine OEMs and MROs.

Chapter 4 (Industrial Field Study) this chapter identifies the components damage modes of currently running aero engine components, Pareto analysis of different damages in different components. What types of repair technologies and process are available? The data collection for repair challenges in industry and how repair selection are conceded.

Chapter 5 (Optimised Repair Selection Strategy) this chapter provides the detail understanding of the challenges in the repair process selection and how ORSS framework addresses these challenges. It also includes the industrial deliverables of selected components, main criteria for selected components, damage modes, and critical repair processes. It also explores the repair knowledge feedback and how repair knowledge sharing framework was developed.

Chapter 6 (Repair knowledge sharing framework) this chapter describe the knowledge sharing and its requirements from repair to design, what and why repair teams want to share with designers. Knowledge sharing framework and its implementation in OEM environments are explored. It also brings the repair knowledge obligations to aero engine designers for effective and efficient knowledge sharing framework for repair focused design.

Chapter 7 (Validation & results) this chapter describes the validation of ORSS framework with three different approaches in the industrial environment.

Chapter 8 (Validation & results) this chapter describes the validation of Knowledge Sharing framework in the industrial environment. The sample of output knowledge is given in Appendix A.

Chapter 9 (Discussion) this chapter discusses the critical points of the research and implication of the two suggested frameworks. How the optimised repair technology /process is selected. How the repair persuaded design can offer further improvements in operational effectiveness and efficiency. It also provides the some critical issues in repair and design approaches within gas/aero turbine OEMs.

Chapter 10 (Conclusions) the conclusion concludes the aim and objectives of the project. How the aim and objectives are fulfilled with knowledge contributions of this project. It also provides the future directions within this research area.

Chapter 2

2 Methodology

The research approach is defined as interpretive in nature to achieve the research aims. This is flexible and interpretive with inductive stage and postulation analysis phase. On the inductive stage the semi structure interviews and focus groups knowledge in repair and design teams are used to collect the repair expert knowledge, repair processes information and components repair knowledge sharing for component designers. This information and knowledge is qualitatively coded for analysis. The developed postulation defined the optimal approach in component repair and repair knowledge sharing obligations. These conjectures of optimised repair strategy and repair knowledge sharing are evaluated by developing a framework for optimised repair strategy and repair knowledge feedback. These frameworks were validated by qualitative methods 'independent field experts', 'focus groups' and 'industrial surveys'.

2.1 Research Design

It was necessary to understand and appreciate the challenging role of repair engineers within aero engine at component level to instigate and completed exploration of the repair / MRO paradigm. To achieve pragmatic understanding of repair and design of aero engine components, it requires the organisations level functional understanding.

The overall research assessment was done in three levels;

1) Formative: it is a method where all the information collected during the research (formal and informal) which was used for building the basic understanding and also used for designing and assessing the systems or procedure (Nichol et al., 2005).

The information of turbine engine, its' design, manufacturing, repair and overhauling are understood with various preferences at each stage.

2) Interim: (instructional, evaluative, and predictive) at this level the guidelines for research; tools/systems/procedures are defined and evaluated furthermore some prediction are also made from previous knowledge. The instructions for tools framework are designed and developed for the researches with rules for the assessment are also anticipated.

3) Summative: At this level the assessment is carried out of the framework, tools or procedures. The main purpose of this level was to validate the proposed frameworks.

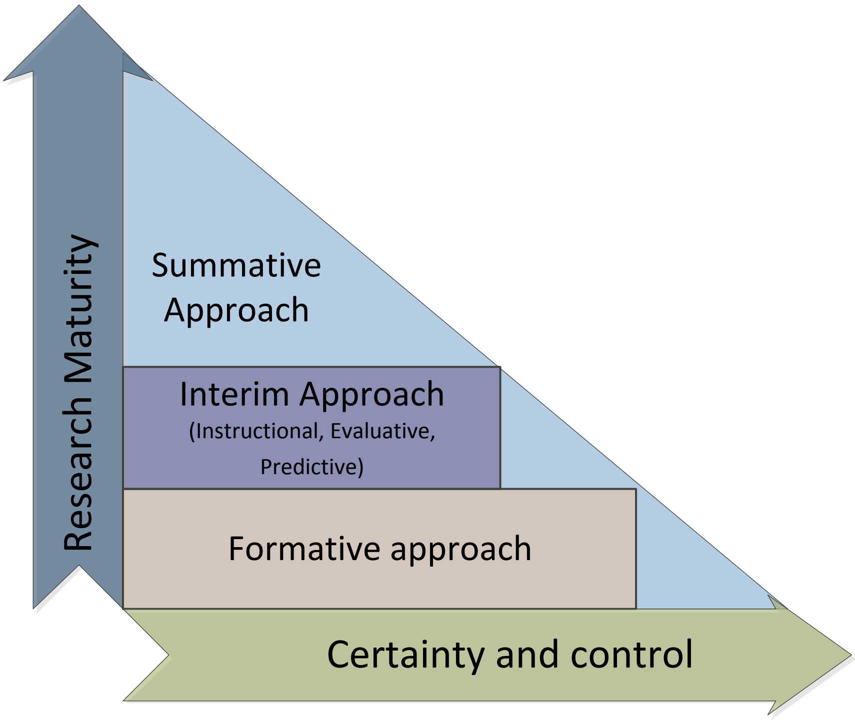


Figure 7: Research design (an update from Hanna and Dettmer, 2004)

Furthermore, semi-structured interviews and participant observation allowed for analysis of current repair procedures within Rolls-Royce and any associated bottlenecks in the repair selection strategy. Due to the confidentiality of the Rolls Royce data and the commercial application of the work, some details have been omitted. A statistical evaluation of the aero-engine component repair dataset will be used to identify failure trends and applicable repair process. The relationship between failure trends and repair process will be critically evaluated to identify design issues that need relaying back to the design team.

Thus, the research is divided into three distinct stages as depicted in the figure below.

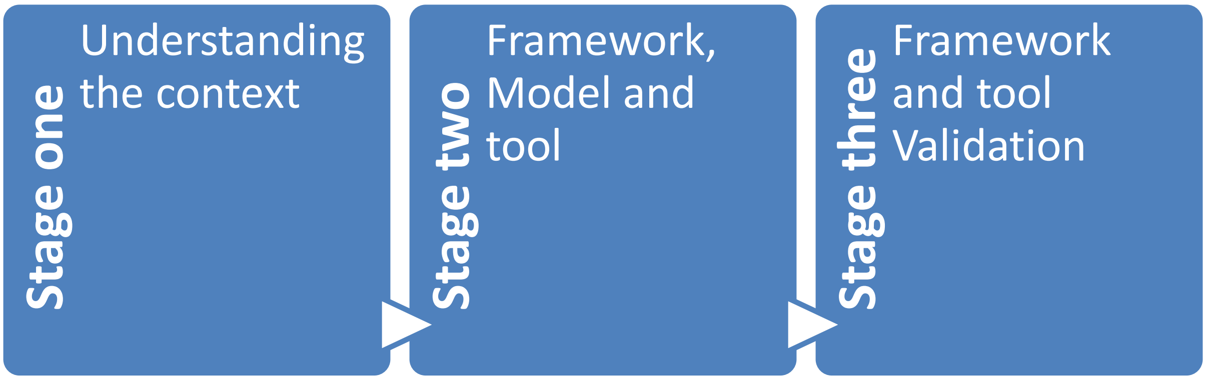


Figure 8 Repair methodology

To develop the understanding of the problem context a detailed literature review has been conducted. This stage relates to the acquisition of detailed knowledge in relation to the aero-engine MRO activities within Rolls Royce and the aero industry.

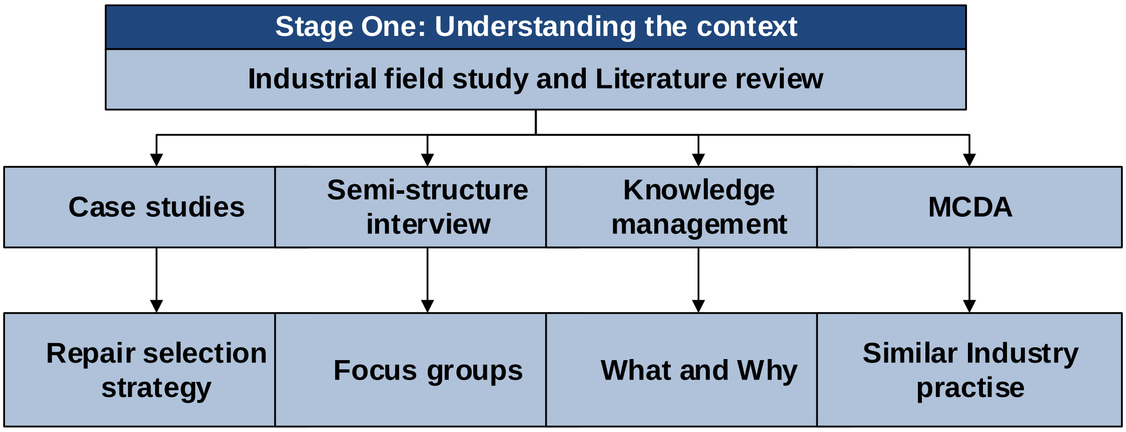


Figure:9 Research methodology part 1

The stage also covers the exploration of existing repair case studies in the aircraft industry.

This stage involved participant observation exercises, analysis of the repair related data from Rolls Royce and general literature. The successful completion of the former two stages yield output that is utilized for development of the framework related to the case studies. Thus, the latter two stages related to the delivery of frameworks and the knowledge contribution of the research.

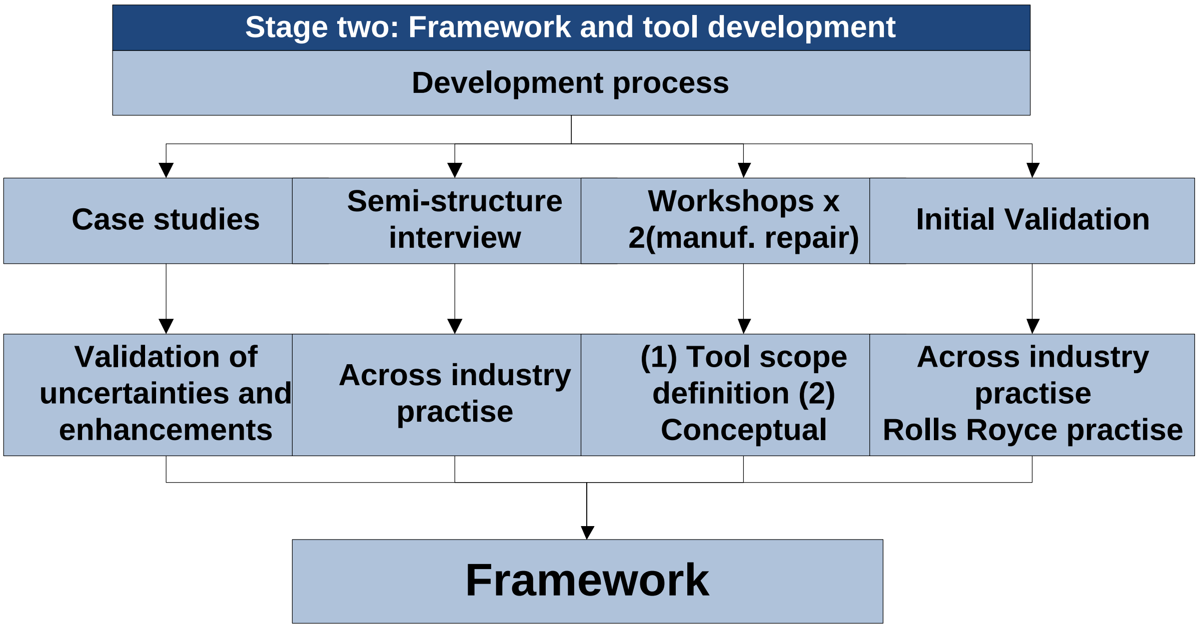


Figure 10: Research methodology part 2

The repair selection and the knowledge feedback to designers is done in a cohesive manner so the learning from the repairs selection can be included in the repair knowledge feedback and vice versa.

The third stage concerns with the development of the framework for repair strategy selection. This stage involved analysis of the framework requirements and its potential applications. The requirements of the model have been captured via various information gathering techniques as depicted in figure below. The case study approach is used for model scope definition and the validation of the functionality.

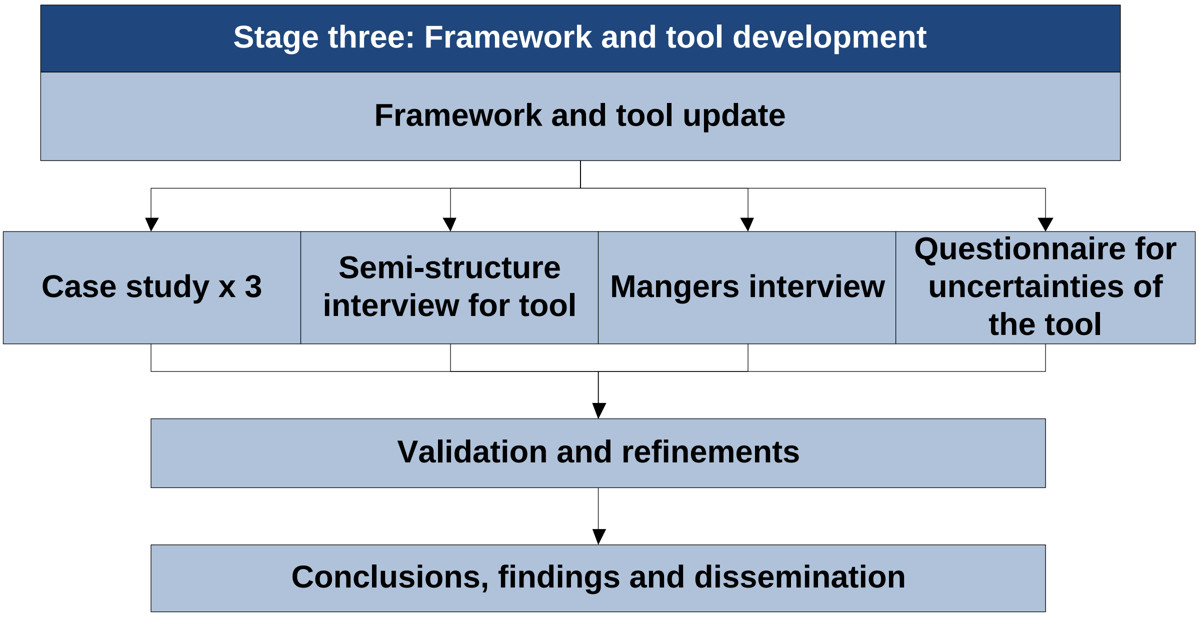


Figure 11: Research methodology part 3

The two components selected for case study by Rolls Royce were:

- Nozzle Guide Vane (NGV)
- Engine Casing

Each case study employed dual stream of work relating to selection of repair process selection and repair strategy though-life of component.

Since both streams include multi-criteria decision making, the associated frameworks are required to support these techniques in addition to the required optimisations.

The research encompasses the following tasks with applicable research methodology.

Table 4: Deliverables with research approach

Task Description	Research Methodology	Data Type	Approach
Capture the bottleneck of aero engine components' repair processes and technologies/	Interview, Questionnaires, Survey	Qualitative	Interpretive
Develop repair selection strategies against repair	Formal Modelling	Qualitative/ Quantitative	Multilevel
Develop optimised repair strategies	Data Collection, Data Analysis, Formal Modelling	Qualitative/ Quantitative	(interplay between data collection & analysis)
Develop a knowledge sharing approach for optimising the repair strategy	Interview/Questionnaires, Data Collection, Data Analysis, Formal Modelling	Qualitative/ Quantitative	Multilevel
Capture the repair knowledge in aero engine design	Interview/Questionnaires	Qualitative	Interpretive
Develop repair knowledge model	Formal Modelling Experimentation Simulation	Qualitative/ Quantitative	Multilevel Scientific
Develop a Visual Demonstrator	Formal Modelling Experimentation Simulation	Qualitative/ Quantitative	Multilevel Scientific

The overall research methodology emerges as a multilevel approach due to diverse the nature of the research at different stages.

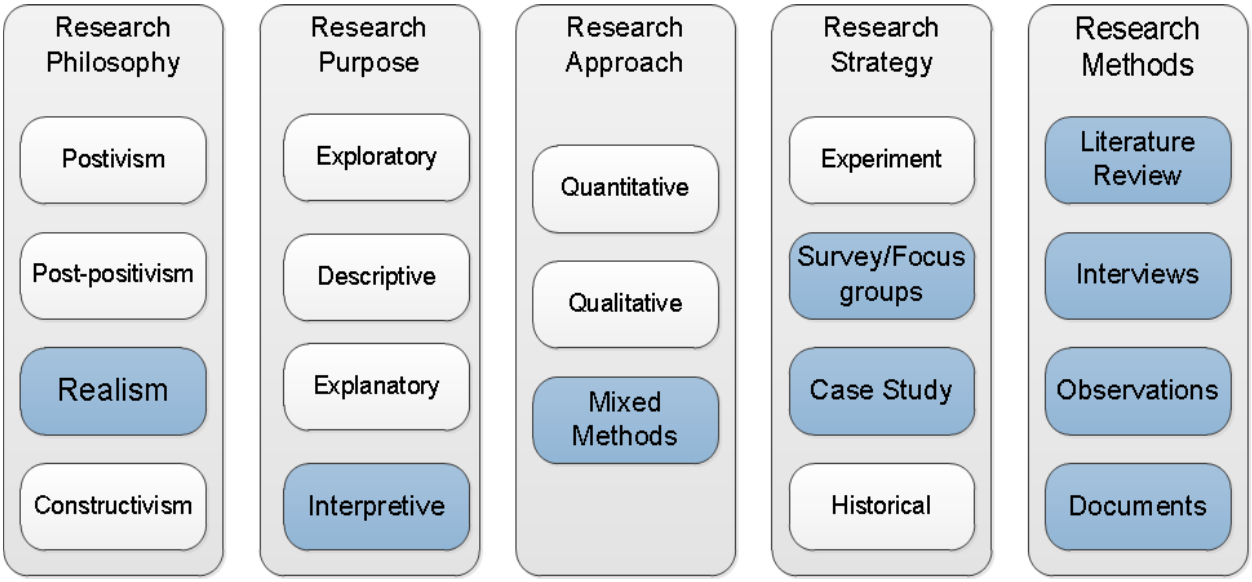


Figure 12: Methodology overview

The nature of the research was industry bases, technology selection for improving the operational efficiency of repair and design teams. Hence the research methodology had to be multi-level, multi-approach with directly influenced by industry.

Chapter 3

3 Literature Review

This chapter provides details of the reviewed literature and discusses the approaches of available literature on this research. This chapter is split into four main areas:

- Multi-criteria decision analysis
- Knowledge sharing
- Synopsis of aircraft gas turbine engine (Aero engine)
- Aero engine (MRO) maintenance analysis

The literature review and the formalisation of the industrial challenges for this project were carried out in parallel. Due to the complexity of the challenges, the methodology focused on the problem solving approach and the particular subjects were selected for the literature review.

This project covers two distinctive areas:

- Repair selection strategy
- Repair knowledge sharing to design

This review discusses the optimised repair strategy selection, repair knowledge modelling, and strategic decision making within repair selection/MRO and cost engineering for large commercial aero engine.

The basic literature review was conducted on the available and forthcoming technologies available for repairs within aero engine MROs. The maintenance sector was the reference point for the study and capturing the data. The approaches for the maintenance of high value assets were taken as a guide for the aero engines. The data of repair processes were studied and different possibilities for value capturing were analysed. E.g. technologies selection to offer advantages over different technologies, but also within same technology, how the process scheduling can offer different benefits were included.

The cost modelling and multi-criteria decision making approaches are also discussed.

In order to develop an optimised repair strategy/repair model, the detailed areas of application need to be well defined and understood.

The Product-Services (servitisation) are incorporated with product-service offerings which provide the value-in-use (Baines, T. S., et al., 2007). To develop these productive services, companies are implementing diverse business models. Fischer et al (2010) divides these models into two 'distinct' methods as given below:

Exploitation: "exploitation of service opportunities through temporal expansion of the service business along the primary customer activity chain." This method offers more service orientated commitments. Therefore business increases by presenting value-adding services (Möller, 2006). One of the best examples for this kind of strategy is TotalCare© from Rolls Royce. "The TotalCare© offering consists of an integrated core set of services covering key aspects of engine management and maintenance, which can be combined with a range of optional services to tailor TotalCare© to an individual customer's requirements"(Rolls Royce).

Exploration: "exploration of service opportunities through spatial expansion and reconfiguration along the adjacent customer activity chain." This kind of approach, exploring new services needs of business and offered those services as an outsourced to saved potential cost to the business, e.g. storage management, data management or security management. Companies implementing this kind of business model increasing their share of revenue attributed to services. However, the prospective profitability, the risk factor increases in this approach (Fischer et al, 2010). Optimization of Maintenance, Repair and overhaul (MRO) activities are of paramount interest within the aviation industry as they have a direct impact on airline performance and profitability. Thus, these MRO activities become the biggest cost driver for the aviation sector.

These MRO activities are further classified within the segments of airframe, engine and component (McFadden, M. et al., 2012). This global market is expected to grow at the rate of 6% estimating to an estimated $43.3 billion in 2013 with nearly 42% of predicted spend on engine MRO segment (McFadden, M. et al., 2012). The engine being the core component of an aircraft is subject to mandatory scheduled maintenance checks as governed by aviation authorities. This scheduled maintenance is mostly driven by flight hours covered by the engine. However, a un-scheduled maintenance may be required due to degraded performance and any damage to the engine.

The modern aero engine is complex mechanical and electrical equipment requiring specialized expert knowledge to perform fault identification and resolution. The fault identification and resolution bears a cost that can be further quantified in monetary and time units.

Financial Impact (FI) = time α monetary cost

These units are proportional to each other as the longer it takes to repair, the more it cost to the aircraft operator. (Murthy, D. N. et al., 2002) reports approx. US 0.5$ million per day as loss of revenue from a Boeing 747 being out of action. Modern diagnostics and prognostics systems aim to minimize the fault identification time and enhance the safety features of the aircraft. A cost benefit analysis of such approach is discussed (Ashby and Byer, 2002), evaluating the benefits of early failure identification within component through the attached sensor. However, the CBA analysis could only be conducted on components for which a failure mode existed and identified by the sensor. Hence, the model is restricted to those components which can be monitored through a sensor.

An RFID based MRO optimization is proposed in the work of Ramudhin et al. (2008), they propose an RFID based parts tracking and control system to increase On Time Delivery (OTD), reduce Turnaround Time (TAT) and control of Work In Progress (WIP). Kleemann, F. C et al., 2013) identify MRO related workshop scheduling issues as an area for optimization and proposed a multi-objective evolutionary algorithm to minimize engine repair times. A similar approach is taken by Stranjak et al. (2008) to optimize the aero engine scheduling by using a multi agent system for scheduling and prediction of engine MRO activities. (Karim, R., et al., 2009) also reported usage of simulation to optimize the workshop capacity issues related to engine MRO activities. Reményi, C., et al. (2014) used simulation models to analyse the maximum repair facility capacity of an engine repair facility.

A traditional aero engine MRO approach is to monitor the degradation of component through manual inspection to predict anticipated repair. An aero engine comprises of various components like shafts, combustors and blades etc. Turbine and Compressor blades within a jet engine are among the most important and critical component that are often subject to excessive work (Yilmaz et al., 2010). Due to this the blades are more prone to different types of damage to the tips and the edges of the blade. Whilst, damages to engine cannot be completely avoided, a suitable maintenance strategy can be utilized to slow down the effects (Kurz, R. and Brun, K. 2007).

3.1 Maintenance, Repair and Overhaul

According to the British Standard Glossary of Terms (3811:1993) "Maintenance" is defined as: "The combination of all technical and associated administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function. This function may be defined as a stated condition." Repair – "Any activity which returns the capability of an asset that has failed to a level of performance equal to, or greater than, that specified by its Functions, but not greater than its original maximum capability. An activity which increases the maximum capability of an asset is called modification (Vozikis, G., et al, 2014). Therefore the repair and maintenance term will be used in correlation. This correlation is vaguely presented as, where the aero engine focusing towards predictive maintenance, which offers them calculated benefits, e.g. fewer repairs for their assets.

It is very important to clarify the project related terminologies in their context to avoid any ambiguity. It was observed that various organisations use the terminology randomly or peculiar to their culture. In some companies the repair can be called asset management to maintenance as repair. As part of the project the basic taxonomy of repair was also considered to minimise the confusion.

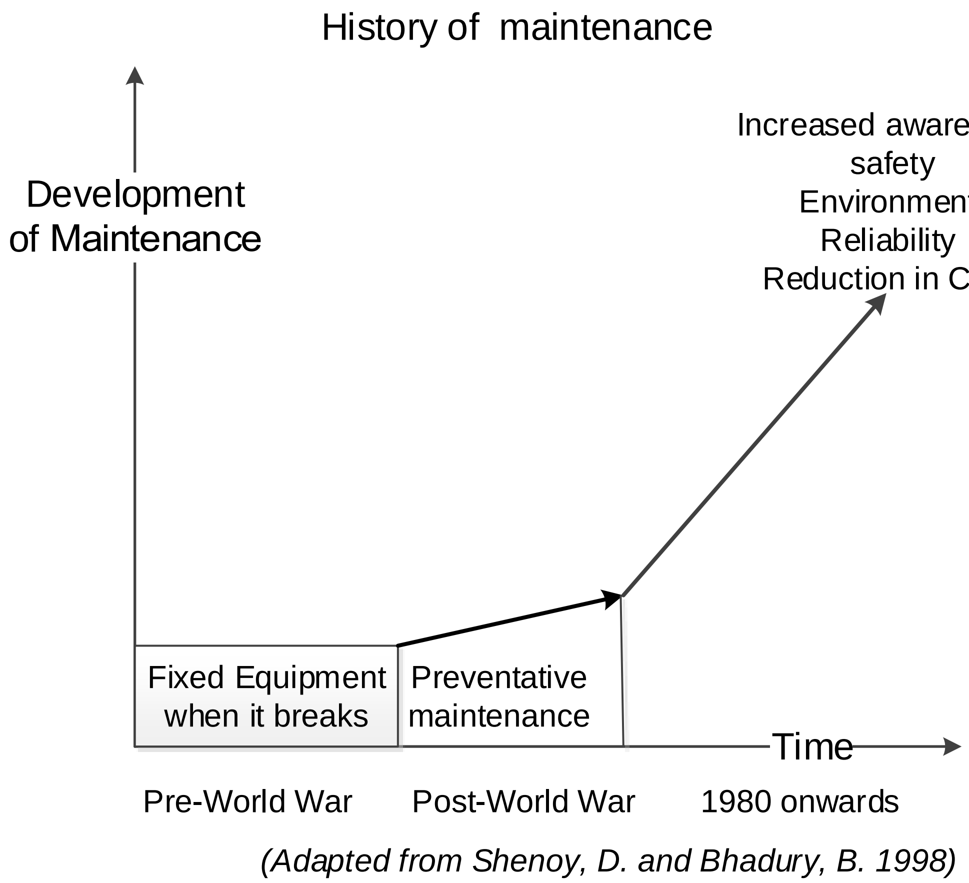


Figure 13: Simplified history of maintenance

The main objectives of carrying out maintenance according to Dekker (1996) are summarized under four main categories:

1. Ensuring system function; availability, efficiency and product quality which is referred to as Overall Equipment Effectiveness (OEE).
2. Ensuring system life (asset management).
3. Ensuring safety.
4. Ensuring human well-being.

The main findings are; no matter which maintenance policy is opted for assets like aero engine it must deal with repair issues. A substantial amount of research been carried out for the maintenance policies. i.e. selecting the maintenance policies from management prospective hence the repair (technical aspect) was neglected. Due to the concept of Servitisation model and its impact on revenues the OEMs (Original Equipment Manufacturers) has gained the interest in technical aspect of repairs.

Therefore, many OEM have embraced the exploitation approach in increasing their service business. Many OEM comprehended that by including a value-creating service factor like maintenance and repair to their product, OEMs can make maintainable customer value which vanguards to increase revenue for the product-service provider (Gebauer et al, 2005). As it is very evident from figure 4, the shift towards services providing that's the value can be created from OEM product to service product e.g. TotalCare® by Rolls Royce.

In essence there are only three OEMs in large commercial aero engine and virtually all of the OEMs are going for "Power by the Hour" exploitation strategy. (e.g. Rolls Royce; TotalCare, GE; OnPoint™, Pratt & Whitney; ADEM™). All of these programmes from all the OEMs are focusing and offering to reduce the repair cost.

As mentioned in the introduction, there is also some evidence which suggests that the servitisation model is playing a significant role in the future of gas turbine, all OEMs are focusing on effective repair strategies. The evidence also suggests that the repair can lead the manufacturing to grow by not repairing the components instead by making gas turbine components less expensive to manufacture by utilising the repair knowledge feedback according to Donaldson G. 2013 global repair services Rolla Royce.

To fulfil customers need, the OEMs (e.g. aero gas turbine) have changed their business model from selling products to selling services (Tuppen and Williams, 2009). Therefore, it has become paramount for companies to provide competitive through life after sales services to their customers.

Currently, the companies are focused to provide maintenance, repair and overhaul (MRO) for the entire life of their components, which ultimately acquires operating and maintaining cost of equipment; enhance the components' availability, durability and reliability; and intensify asset value and customer desirability (Rolls Royce, 2012). However, the companies are not adequately equipped to provide the extent of services that customers may require. The new techniques and methods can be employed to enhance the efficiency and effectiveness of MROs, and to gain more revenues (Deloitte, R., 2012 and Visiongain, 2011). These new methods and techniques may include cost-benefit analysis, better decision making in alternative repair technology selection (i.e. multi criteria decision making or analysis) and an improved repair knowledge model for designers.

The OEMs are also focusing to develop and manage their design knowledge and design knowledge feedback to control more cost and to increase their profits from their revenues.

This is where design team and repair team are trying to turn every stone to get more control on the cost and prolong their products specially to reduce the cost from the support strategies.

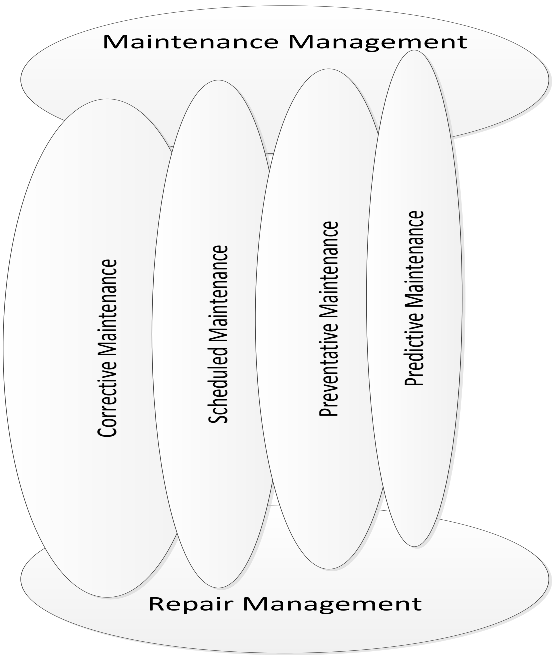


Figure 14: Link between maintenance policies and repair

The methodical approach to maintenance/repair management has started before 1950's but main literal start was from the 1950's and the 1960's (Kelly, 1989; Pintelon and Gelders, 1992 Maintenance Management in Network Utilities). Maintenance was always reflected as a support function and therefore its cost was considered as a burden. Operational research techniques for maintenance/repair planning materialised in the 1960's and more enhanced maintenance strategies like condition monitoring came in to use by the 1970's. The maintenance/repair has developed into many branches like reactive, preventive, proactive approaches and predictive maintenance (British Standard, 1984; Bateman, 1995; Lee et al, 2000; Swanson, 2001 and Waeyenbergh and Pintelon, 2002). There are no particular methods for maintenance /repair considered best for every situation. Methods of repair and maintenance are determined situation as situation suites.

For the simplicity the maintenance can be categorised as:

Table 5 Maintenance Strategies

Maintenance Strategy	Definition	References
Reactive Maintenance	"Run to Failure" maintenance mode. No maintenance is done unless the machine breaks down.	(Swanson, 2001)
Preventive Maintenance	"The maintenance carried out at predetermined intervals or according to prescribed Criteria and intended to reduce the probability of failure or the degradation of the functioning and the effects limited."	(British Standard 3811, 1993)
Corrective Maintenance	"Those actions are only performed when a machine breaks down. There are no interventions until a failure has occurred."	(Bevilacqua and Braglia, 2000)
Predictive Maintenance	"Maintenance carried out according to need as Indicated by condition monitoring.	(British Standard 3811, 1993)
Proactive Maintenance	"Systematic approaches that can continuously track health degradation and extrapolating temporal behaviour of health indicators to predict risks of unacceptable behaviour over time as well as pinpointing exactly which components of machine are likely to fail."	(Lee et al, 2006)

3.2 Background

Products' after sales service programs provided by OEMs (original equipment manufacturers) referred as servitisation increase customers' asset utilisation and ultimately effect on market capture by the OEM. To fulfil the customers need, the OEMs (e.g. aero gas turbine) have changed their business model from selling products to selling services (Tuppen and Williams, 2009). Therefore, it has become paramount for companies provide competitive through life after sales services to their customers.

Currently, the companies are focused to provide maintenance, repair and overhaul (MRO) for the entire life of their components, which ultimately acquires operating and maintaining the cost of equipment. It enhances the product availability, durability and reliability; and intensifies asset value and customer desirability (Rolls Royce, 2012). However, the companies are not adequately equipped to provide the extent of services that customers may require. The new techniques and methods can be employed to enhance the efficiency and effectiveness of MROs, and to gain more revenues (Deloitte, R., 2012 and Visiongain, 2011). These new methods and techniques may include decision making in alternative repair technology selection (i.e. Multi criteria decision making or analysis) and an improved repair knowledge sharing for designers.

The strict standards within the aerospace industry, highly skilled workforce, high operational cost and huge commitment of infrastructure for MROs activities are the potential threat MRO business. Furthermore the new investments from developing nations are making the competition more aggressive. There is no competitive formal repair selection method in the aviation MRO industry, which satisfies the upcoming challenges. To mitigate these challenges repair selection techniques will assist the MROs to be more competitive.

3.3 Repair context

Before carrying out the research the context of repair needed to be rationalised for common understanding across all the stakeholders. The aviation industry uses MRO as a generic term for maintaining an asset and different organisations have their own understanding, i.e. asset management, asset utilisation or operational strategy of assets. In any case, repair is a central /common part of any maintenance strategy.

Maintenance strategies like: Corrective, schedule/preventative and predictive/ monitored all have repair as a necessary part

Table 6 Repair context in maintenance strategies

Maintenance strategy	Corrective	Scheduled	Preventative	Predictive	**Repair** (Repair is a necessary element of all maintenance strategies)
Components required	Low	High	Medium	Medium/low	
Labour	High	Medium	Medium	Medium/low	
Time	High	Medium	Medium	Medium/low	
Resources	High	Medium/low	Medium	Medium/low	

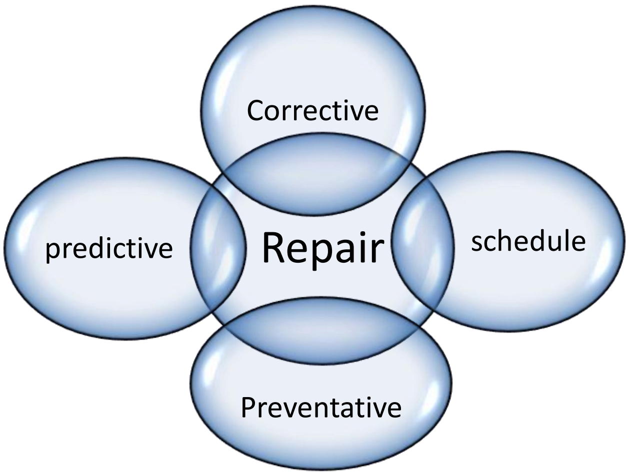


Figure 15: Repair as a central part of maintenance strategy

Furthermore, all research, literature and industry expert are suggesting the strong need to develop a complete optimised repair selection strategy which addresses all the challenges from top to down i.e. business to technical.

3.4 Current repair technology selection in RR

Rolls Royce is a reputable leading company and repair of large aero engine is divided into two categories; source controlled and non-source controlled.

The source controlled repairs are those which need to be certified before implementations. These are safety critical to the design of the aero engine and needs strict procedural controls and needs joint ventures to outsource. The non-source controlled repairs are based on the processes' capacity and compatibility and can be easily outsourced.

The engine repair process from top to down, which are the main focus of this research. As far as the repair processes are concerned, the repair processes are gradually developed for specific components and selected on a capacity basis in the engine shop based on the components. There is no specific procedure for the repair process selection apart from the expert opinion.

3.5 The Challenges and Context of research

In an effort to make MRO business more effective, the steps to manage change in MRO business are vital. The challenge for the industry is to develop a repair process selection framework which considers the business and technological benefits for repair selection strategy. Implementation of the new process is limited in terms of optimising the selection. The current decision making in repair is technical expertise based selection process which does not utilise the formal techniques like multi criteria decision making techniques.

Rolls-Royce Repair Team is committed to identify optimise repair / remanufacturing processes and technologies, and feedback to design engineers for supporting life cycle design of aero engine. Currently there is a need of an approach and a tool that can be used to optimise repair strategy for aero engine damage; and also a need for efficient and effective repair knowledge share at the design stage.

In an effort to make MRO business more effective, the steps to manage change in MRO business is vital. The challenge for the industry is to develop a repair process selection model which considers the business and technological benefits for repair selection strategy. Implementation of the new process is limited in terms of optimising the selection. The current decision making in repair is technical expertise based selection process which does not utilise the formal techniques like multi criteria decision making techniques.

The scope of the research is also not to develop new repair method, but selecting the best/optimised repair process with multiple options.

As the aero engine design complexity and higher demands are growing, the MRO $50 billion industry's with over 7% growth the challenges are also increasing, the MRO knowledge sharing may be the answer (IATA 2011). The world growth in air traffic is bringing large MRO investment and knowledge sharing will play a crucial role in the MRO development in many regions. The knowledge sharing improves efficiency, competitive new design and technology in MRO (Weingartner, 2010)

As previously mentioned that servitisation have changed and changing the aero engine market, new engines need to be effective in service life. The repair knowledge sharing in service life will benefit the future design to be more competitive, which Rolls Royce also investing.

There are many benefits and mostly acknowledged by industry, the main challenge is creating and sharing the knowledge to benefit. When, what and why (3w) were analysed by Rolls Royce to address this challenge. Two different groups were consulted (repair and design) and many times among these two groups were providing the expertise. The repair engineer expert knowledge gained from component repair, repair processes, capacities, learnt lessons, known malfunctions, incidences and accidences, design updates, and material and processes updates are some of the factors to make component repair decisions in complex environments with problem solving skills. These inputs of repair engineer are not part of manual or available in any media. The expert repair engineer also deals with many unique situations within complex repair, selects the repair processes and different repair technologies for the future to keep the repairing competitive.

3.6 Multi-Criteria Decision Making

Multiple-criteria decision-making (MCDM) or sometime also referred as Multiple-criteria decision analysis (MCDA) is a field of operation research. MCDM cogitates the decision making where multiple criteria exist for every decision, often contradicting each other. The main aim of this research is to find the most suitable solution for a given problem at a given time with its unique circumstances. Hence some decisions are better than others, not simply right or wrong.

The research community has employed MCDA extensively in recent times, some findings are given in graphs to illustrate and cover the best use of similar approaches in different industries of this research in brief.

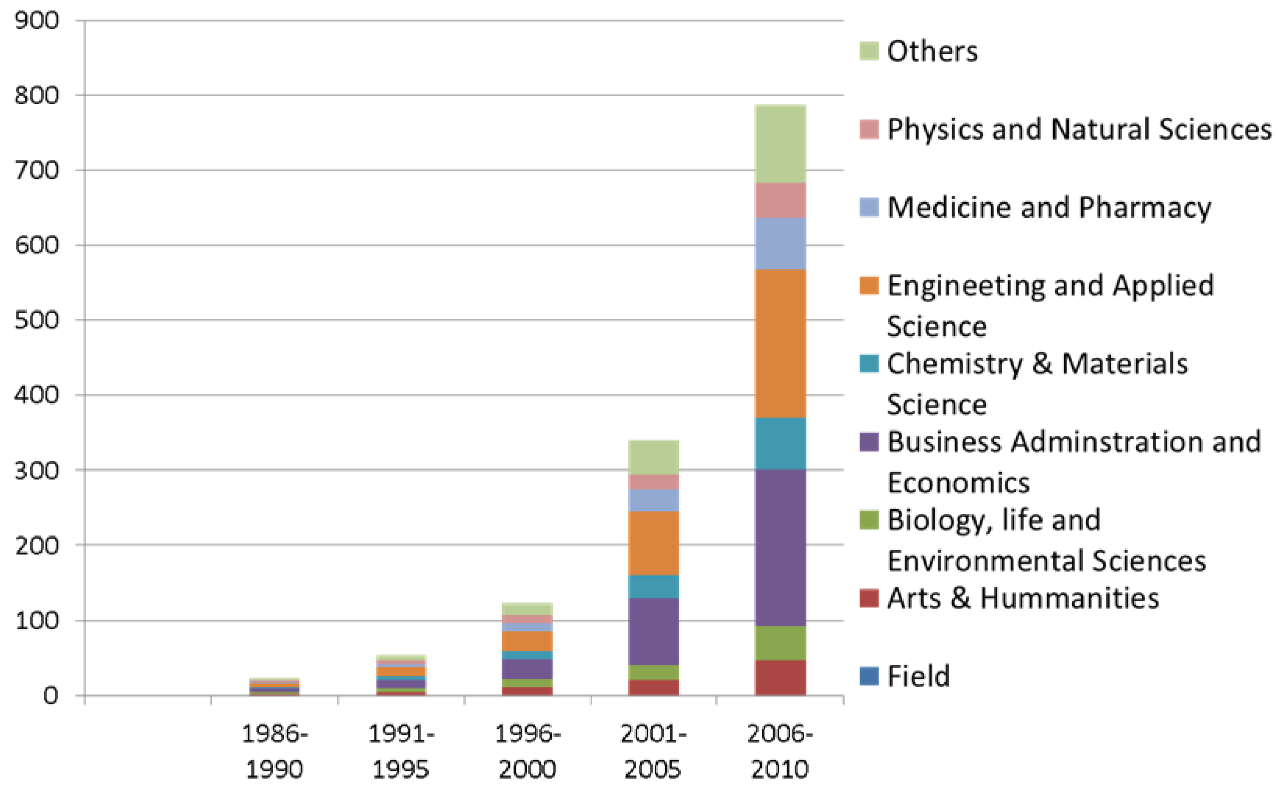


Figure 16: Use of MCDA in published literature

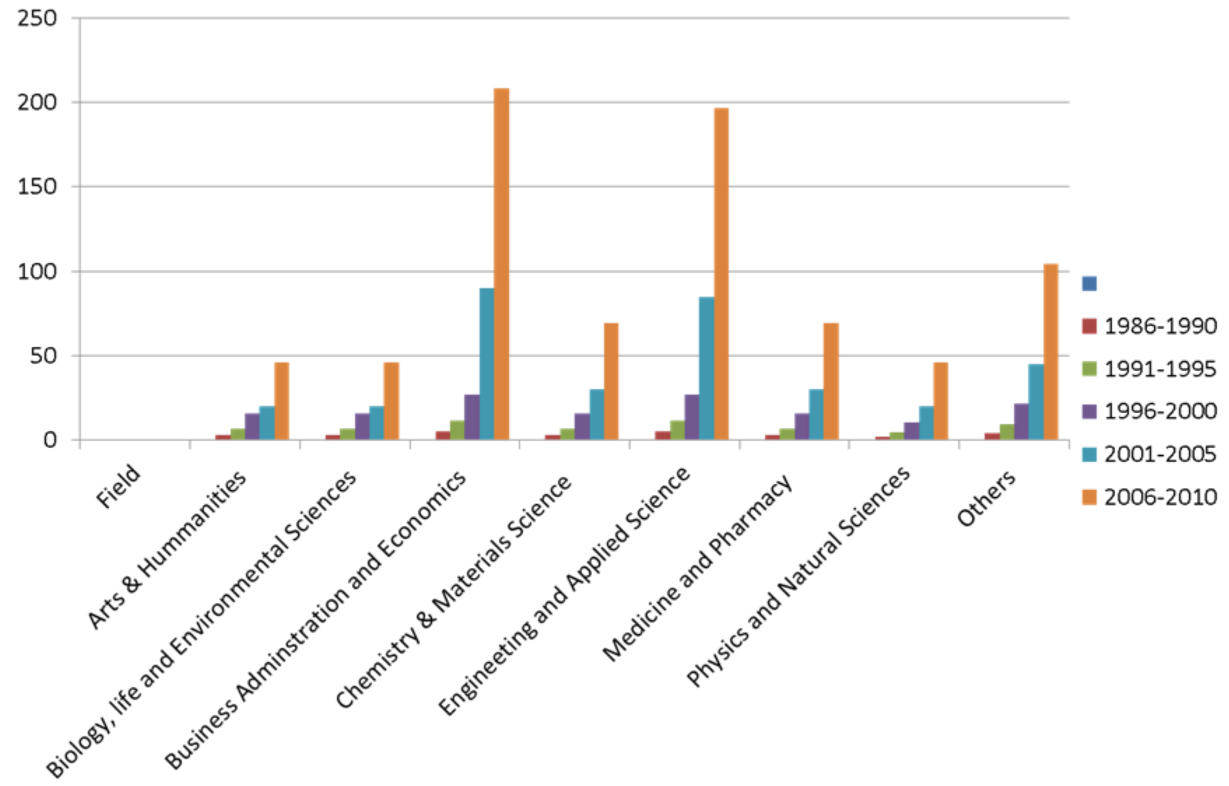


Figure 17: Increasing applications of MCDA in different industries

A comprehensive study on "multiple Criterion's decision making" in context of repair decision has grown in importance to gain a competitive edge in the industry, therefore many MRO organisations are trying to implement a framework to utilize the technique. Decision making has become more important in repair management as the scope of studies has broadened both in terms of planning objectives and the number of interested stakeholders. The choices of appropriate repair involve numerous quantitative and qualitative considerations reflecting the values of multiple stakeholders, which often make the decision-making process complex and contentious. Therefore, there has been an increasing and deliberate emphasis to involve stakeholders in repair/process planning and management decision making, including participation in the analytical modelling process. Such stakeholder involvement is believed to lead to a more efficient decision-making process. There are a variety of ways in which Multi-objective decision models can be blended to support repair process and methods.

Certain areas of maintenance industry are already using techniques called AHP (Analytic Hierarchy Process) for decision making, and from the initial literature review, AHP deemed the most suitable for the repair strategy selection because it offers several advantages such as it is user defined and can also deal with tangible and non-tangible parameters.

Decision Making Support is based on multi-criteria decision analysis (MCDA) and its variants are listed in table below.

Table 7 the capacities comparisons of different techniques

Supported MCDA method(s)	Pair-wise comparison	Time analysis	Sensitivity analysis	Group evaluation	Risk management
PAPRIKA	Yes	No	Yes	Yes	No
AHP	No	No	Yes	No	No
MAUT	Yes	No	Yes	Yes	Yes
MAUT, ROMETHEE	Yes	No	Yes	Yes	Yes
AHP, MAUT	Yes	No	Yes	Yes	Yes
AHP Adv.	Yes	Yes	Yes	Yes	Yes
AHP, ANP	Yes	Yes	Yes	Yes	Yes
ELECTRE	Yes	No	Yes	Yes	Yes

The scope definition from the expert focus group as mentioned earlier AHP (analytical hierarchy decision analysis) techniques of MCDA was selected to be adapted for the optimised selection of repair technology/process.

Table 8 MCDA technique comparison vs expert's scope definition

MCDA Techniques	Quantified criteria	Non-Quantified criteria	No of criteria	Complexity
AHP Saaty, 1972)	Flexible	Flexible	Flexible	**less**
MAVT/MAUT (Keeney et al, 1976)	Flexible	Less flexible	Less flexible	**Moderate**
TOPSIS (Hwang et al, 1981	Flexible	Less-flexible	Less-flexible	**High**
ANP (Saaty, 1996)	Flexible	Flexible	Non-flexible	**High**
VIKOR Opricovic, 1998)	Flexible	Less-flexible	Non-flexible	**High**

3.7 AHP theory

AHP is multi-criteria decision making technique which assists the decision maker fronting a complex decision with various often contradicting and subjective criteria. In this research, optimised selection criteria are required to achieve best performance, where all the criteria are important and subjective.

, Analytical hierarchy process is mathematically based on the eigenvectors; a set of eigenvector of linear function, respectively paired with its parallel eigenvalue is called Eigen system. The eigenvector are the non-zero vectors of a square matrix, which remain proportional to the original matrix after multiplication i.e. any vector X which satisfy the equation (Eq 1)

$$x(A - \lambda I) = 0 \tag{1}$$

To find eigenvector of a matrix the eigenvalue must be found, hence the equation can be written as shown in equation 2. The vector x is common and equation is expressed as described in equation 2.

$$x(A - \lambda I) = 0 \quad (2)$$

Only method to solve this is if A-λI does not have inverse, (if A-λI)$^{-1}$=0, i.e. the only solution is zero vector). Therefore we determine the value of λ which is the determinant of A-λI is zero (Eq 3).

$$|A - \lambda I| = 0 \quad (3)$$

Once the eigenvalues are found, the values can be substituted back into the original equation to find the eigenvectors.

Using this technique the quantities can be transformed into matrices and solving for eigenvector the solution can be found.

Therefore largest eigenvalue will drive the eigenvector from recurring function of the matrix to an arbitrary vector result in a vector proportional to the eigenvector (Weisstein, E. W. (2002).

$$\lim_{n \to \infty} A^n y = \lambda_1^n b_1 x_1$$

Table 9: AHP in different industries

Author	Techniques	Industry	Maintenance strategy	REMARK
M. Bevilacqua et. al. (2000)	AHP with sensitivity analysis	oil refinery	Corrective Preventive Condition-based Predictive	Assets are in Identical groups
Stefan Gassner (2003)	Experts' input based AHP	Wind Turbine Industry	Multi Dimension maintenance strategy	An approach based on the value chain
Bertolini and Bevilacqua (2006)	Hybrid AHP	Oil refinery	Corrective Preventive Predictive	Cost and time comparisons among strategies
Ling Wang (2007)	Hybrid AHP	Power plants	Corrective Preventive Condition-based	Considered as simplest and easiest
M.S. Zaeri (2007)	Hybrid AHP	Manufacturing	Corrective Preventive Condition-based Predictive	An approach based on the value chain (Multi factors)
K. Shyjith et al (2008)	Hybrid AHP	Textile	RCM Preventive Condition-based Predictive	Finding the best solution
N.S. Arunraj (2010)	Hybrid AHP	Chemicals	RCM Preventive Condition-based	Factoring Risk in maintenance
Alirza Ahmadi (2011)	Hybrid AHP	Vehicle systems	Corrective Preventive Condition-based	Introducing prognostic health maintenance
M. A. Burhanuddin (2011)	AHP	Food	Corrective	MCDA (Multi criteria decision analysis)

3.8 Knowledge Feedback for designers of aero engines

From previous section it is very clear that the OEMs are aiming to reduce the cost from their design and MRO practices to maximise the profits. The difference of data, information and knowledge has been discussed by many.

The knowledge comes in many different shapes and sizes, the explanation given by Oxford dictionary is: “Facts, information, and skills acquired through experience or education; the theoretical or practical understanding of a subject”. But in the technical world definition varies even more due to the soft aspect of its contextual understanding.

Some of the knowledge oriented research definitions to illustrate the above mentioned theme.

Table 10 Definition of knowledge in different context

Term	Definition	Author
Product Development (PD)	*"The set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product"*	(Ulrich and Eppinger, 2008).
Product Development Process (PDP)	*"The sequence of steps or activities which an enterprise employs to conceive, design, and commercialize a product"*	(Ulrich and Eppinger, 2008).
Lean Product and Process Development (LeanPPD)	Lean PPD is a systems approach to the development of products and their associated production processes, which focuses on the creation of value, and results in the elimination of waste. This is achieved through enhancing a stream of activities, so that decisions are made based on acquiring knowledge.	Lean concept in product and process development (Considered to be new field in Lean concept development)
Knowledge Based System (KBS)	*"A knowledge-based system is a comprehensive computer program which solves problems within a limited and specific field, using data on the problem, knowledge related to the problem, and "intelligent" decision making capabilities"*	(Karray and De Silva, 2004).
Knowledge Life Cycle (KLC)	*"A process that produces knowledge with a conceptual framework that provides a cognitive map of these processes"*	(Firestone and McElroy, 2003).
Lean Thinking (LT)	Lean is a generic philosophy focusing on the elimination of wastes, the creation of value and continuous improvement of processes within an organisation.	Womack and Jones (2003).
Knowledge Management (KM)	*"Knowledge Management is about managing the KLC"*	(Firestone and McElroy, 2003).

Similarly, knowledge types are defined in many different ways, but two fundamental kinds, as per the majority of the researchers are (Ikujiro Nonaka 2008);

- Tacit knowledge
- Explicit knowledge

Knowledge engineering established methodologies:

- CommonKADS
- SPEDE
- MOKA

The literature suggests that, The Knowledge Based Engineering (KBE) has been the approach for many manufacturing and design knowledge feedback models. David Baxter in 2007 has supported a process-based approach in knowledge reuse and MOUNTNEY; S. 2009 suggested developing the structure of required knowledge. In any case it is important to develop the consensus with design and repair to cohesively understand what they want, how they want it, when they want it and more importantly what it means when they get it.

These bring the concept of pull and push philosophy in manufacturing, which can be helpful in knowledge feedback in repair. Knowledge management firms use the figure below as an explanation; the divide between in tacit and explicit knowledge in relations to pull and push philosophies in regards to knowledge which has been an important tool for knowledge sharing.

Figure 18: KM Boston Square (Milton, N. 2015)

This figure can be adapted as to explain industry specific resources

	Push	Pull
➢ Focused	• Manuals, • Training • Bulletin • Updates	• Probe the expert
➢ Disseminated	• FAQ • Industrial cases • Blogs	• Q & A sessions

Figure 19: KM Boston Square for resources focus (Milton, N. 2015)

In the aviation industry, the knowledge sharing must be assisted by taxonomical understanding to deliver focused knowledge feedback. The challenge in knowledge sharing may depend on the effectiveness of skills and complexity in knowledge, It must be assisted by some input of error detection is explained by Rucci 2010 in sports. (Rucci and Tamporowski, 2010)

3.9 Modular Engine Design

Due to the maintenance, high throughput and efficiency in design and manufacturing the modular design approach is adopted.

Typical Rolls Royce aero engine is made up of 8 different modules.

Module 1 (LP compressor & turbine)

Bypass fan, the Low pressure (LP) compressor with its drive shaft is part of 1 module. The drive shaft is driven by LP turbine. The rotor is constructed of dovetail slits or fir tree for the bypass fan blades. The latest engines are trying to minimise the bypass fan blades from early RB211 three spool engine 33 blades to 20 blade three spool engine RR Trent 1000. The construction of these fans is very advance and made from hollow titanium and some other fan are made from carbon composites. (Courtesy of RR)

Figure 20: Module 1 Courtesy of RR

Module 2 (Bearing & IPCs)

It consists of bearing housing, which holds the IPC (intermediate pressure compressor) and LP compressor. IP compressors are group of disks and blades into a cylinder and made in the form of bliss or bladed disk, which is a single part construction of blade and the disks to save weight and improve engine efficiency. Disadvantage in such construction, whole blisk needs dismantled and repaired from any damage (Courtesy of RR)

Figure 21: Module 2 Courtesy of RR

Module 3 (intermediate case)

Between the IPC and HPC lies the intermediates case. It is constructed from internal hollow struts of which provide access to accessories like gearbox drive shaft, cooling air and other tubes. This intermediated case is also providing the location bearing for the shafts. (Courtesy of RR)

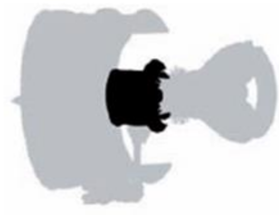


Figure 22: Module 3 Courtesy of RR

Module 4 high pressure (HP) System

Essential a cylinder providing the HP systems comprises of inner casing combustion systems, HP compressor and HP turbines. Previous design had co-rotating design and latest design has contra-rotating design.

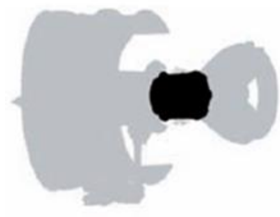


Figure 23: Module 4 Courtesy of RR

Module 5 (Intermediate pressure turbine (IPT))

This module includes the turbine casing, blades, nozzle guide vanes (NGV), turbine disk shaft and bearings for intermediates and high pressure shafts, Where NGVs are attached on casing. It also houses some instruments for EGT (Exit gas temperature), very important to examine the performance of the aero engine.

Figure 24: Module 5 Courtesy of RR

Module 6 high speed gearbox (HSGB)

This module provides power for the accessories for the engine and the aircraft like fuel pumps, hydraulic pumps, electrical generators, etc.. This module is installed onto the LP casing.

Figure 25: Module 6

Courtesy of RR

Module 7 (Bypass fan case)

This is the largest module of the aero engine; it is constructed from metal cylindrical ring or and composites and houses the NGV. Main aim of this case is to contain the bypass fan failure.

Figure 26: Module 7

Courtesy of RR

Module 8 (LPT)

LPT uses the hot gases energy to drive the bypass fan which provides around the 80% of the thrust of the engine. It is consists of disks and blades and the LP turbine shaft which drive the bypass fan.

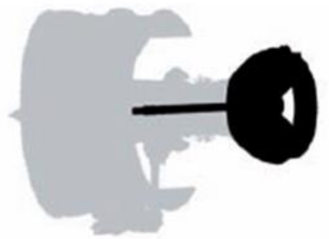


Figure 27: Module 8

Courtesy of RR

3.10 Engine operations

Each module has precise operating condition of the engine to perform effectively and efficiently according to the engine design, hence to monitor each module conditions are very important for safe and effective operations.

There are many gauges which provide the necessary readings to monitor engine conditions. All revolving components have the rotational speed monitors, which can monitor the thrust (FAA Handbook 2004). The engine efficiency highly depends on the engine pressure ratio (EPR) which is calculated from the intake pressure to the turbine exit pressure.

As aero engines are heat engine and materials used in them has temperature limits and need to be monitored, inlets and EGT are measured for reliable monitoring as it is very difficult to measure the instantaneous HPT temperature.

EGT is one of the most important parameters to monitor the engines' health; it is also used for engine efficiency. High EGT is the prime indicator for aero engine deterioration. The engine deterioration is measured by the maximum tolerable EGT to take-off EGT, lower the difference the higher the deterioration (MTU, 2014).

Having modular design, the manufacturers of large aero engine have different teams and commodity teams responsible for each module in design, service and maintenance phases of the engine.

3.11 Aero Engine Maintenance

The overview of the aero engine maintenance is discussed. Aero engines are very complex, high precision and major part of the aircraft. The cost aspect of the aero engine makes it more complex from the operational management and planning aspect of the aircraft availability.

The aim of every engine maintenance program is to maximise the engine on-wing time to maximise the asset's utility, keeping the engine safe and in operating condition at all times because aircraft in the air is earning revenues and without the engine aircraft is not profiting asset quite the opposite.

Aero engine maintenance can be split into four different stages

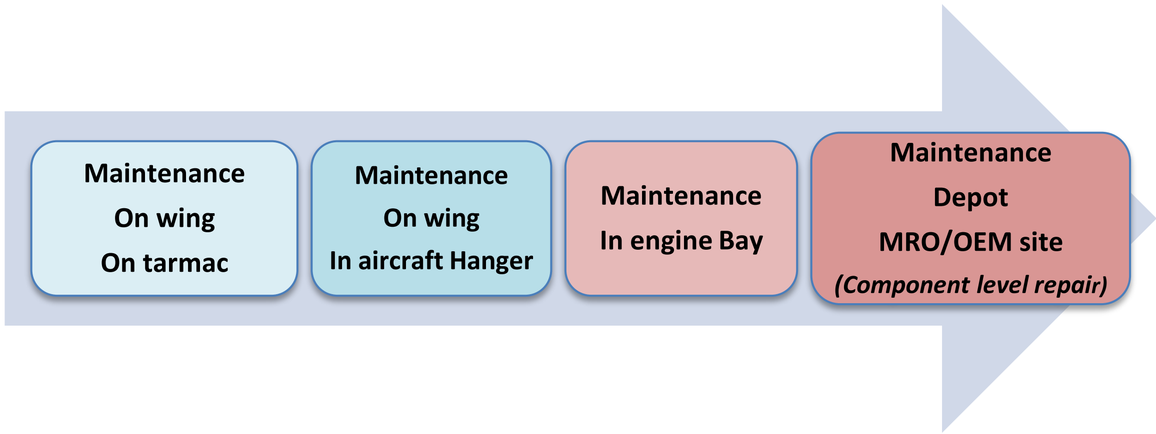


Figure 28 Aero engine maintenance stages

Maintenance (On wing on tarmac)

On wing maintenance also referred as in-line maintenance is the most preferred option for the operators where the aircraft does not lose any air time and gets all required maintenance while parked at the gate. Nowadays all aero engine manufacturers have engine condition monitoring telemetry. By this method engine condition and parameters are monitored anywhere and can be maintained anywhere. If engine need any update or require any maintenance it can be provided, this is not only safe but also very effective for the operators. It also provides valuable inputs and training to aircraft pilots to maximise the engine potential. Any cause of concerns, an engineer can also inspect the engine while parking at the gates.

Maintenance (On wing in aircraft Hanger)

Maintenance on the wing in the hanger refers to any maintenance action are required when the aircraft is in hanger due to specialised tooling or component replacement. This is normally is scheduled maintenance so aircraft does not lose any air time. The engine maintenance can be done with aircraft maintenance. The aircraft manufacturers also demand the regular maintenance like A, B, or C checks.

Maintenance (In engine Bay)

On some occasions engines are required to be detached from the aircraft to carry out maintenance or repair activity which cannot the done while the engine is on the aircraft. The common cause for this kind of action is scheduled repair, incidental or accidental damage repair.

Maintenance (Depot MRO/OEM site ***(Component level repair))***

All aero engines are designed to last around 20-60 year based on their operations. The manufacturer like Rolls Royce aero engine needs to be overhauled after 3000 flights, where each flight includes take-off, cruise of 5-18 hours and landing. It is also a legal requirement like: EASA 145 and NPA 2011-15 EASA – Europa

This is a component level maintenance, repair and overhaul (MRO) of aero engine where the engine is taken off the aircraft and sent to MRO/OEMs facility where teams of engineers and technical dismantles the engine, repair all the components as required by the manufacturer and assemble and test the engine to the required parameters before sending back to the operator.

The excessive and /or harsh use of the engine can deteriorate the engine to the extent where the engine may need overhauling.

The deterioration of the components in aero engine affects the overall efficiency of the engine, hence the thrust of the engine decreases over time, to meet same thrust rating the engine has to work harder, which mean hotter, if the engine gets hotter and hotter the EGT margin gets reduced and engine becomes less efficient.

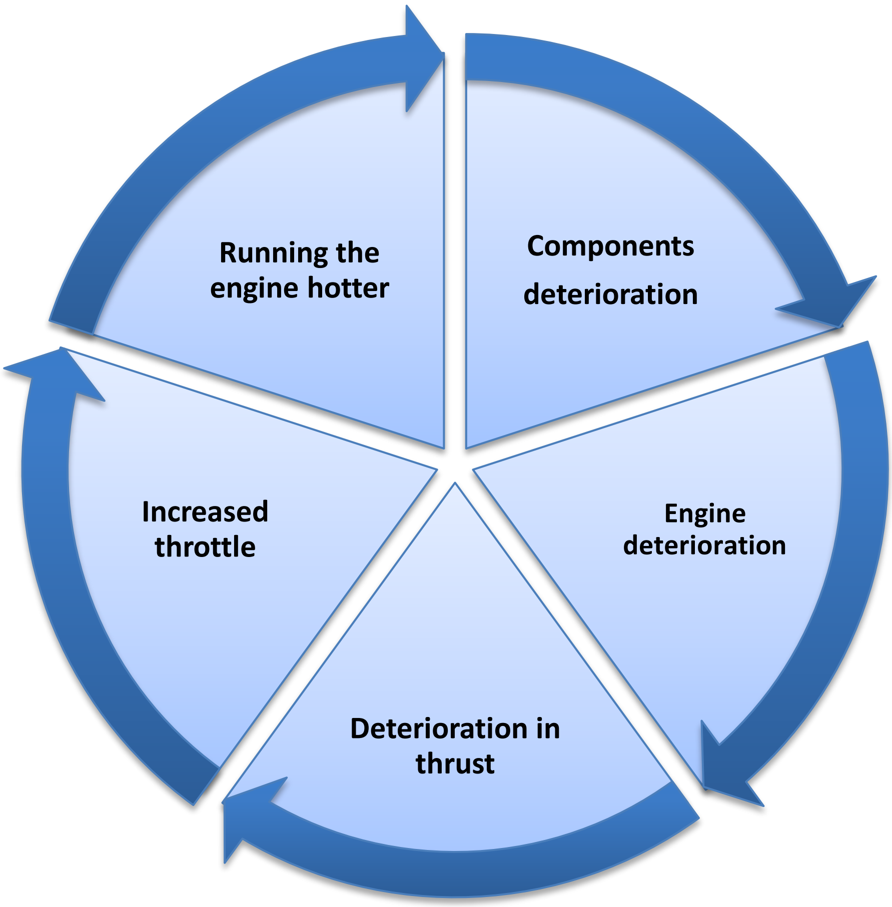


Figure 29: Engine deterioration mechanism (Ackert, S., 2011)

The EGT margins regain may also require engine overhauling as the effect of engine deterioration illustrated in the given figure (Ackert, S., 2011).

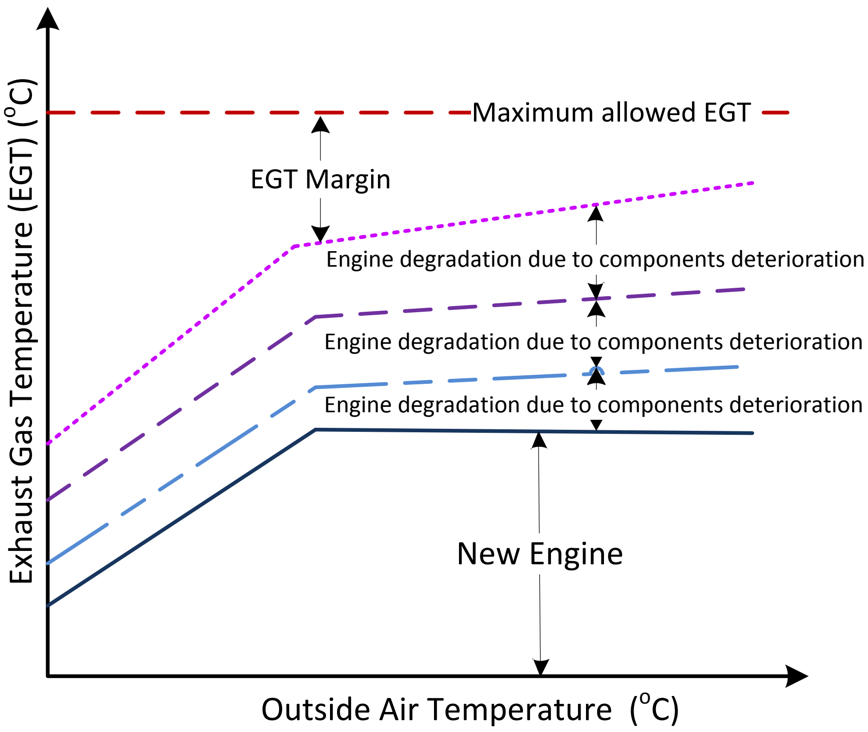


Figure 30: Effect of engine deterioration on EGT (Ackert, S., 2011)

The industrial study was done to understand the repair of the components in greater details at MRO/OEM facility later.

The next chapter investigate the component level challenges faced by the repair teams

Chapter 4

4 Industrial Field Study

4.1 Introduction

In the earlier chapter, the critical literature review was conducted to recognise and envisage the influencing factors and decision methods which could be beneficial for the research. The goal is to comprehend current selection method to repair and industrial prerequisite for the repair selection framework, including the research question RQ4 to RQ6 mentioned in an earlier chapter. It is also anticipated that there may be other industrial concerns related to these research questions.

The semi-structure interviews supplemented with questionnaire were selected to be the most suitable method to achieve the research goals. The overall approach of this chapter is depicted in the figure below

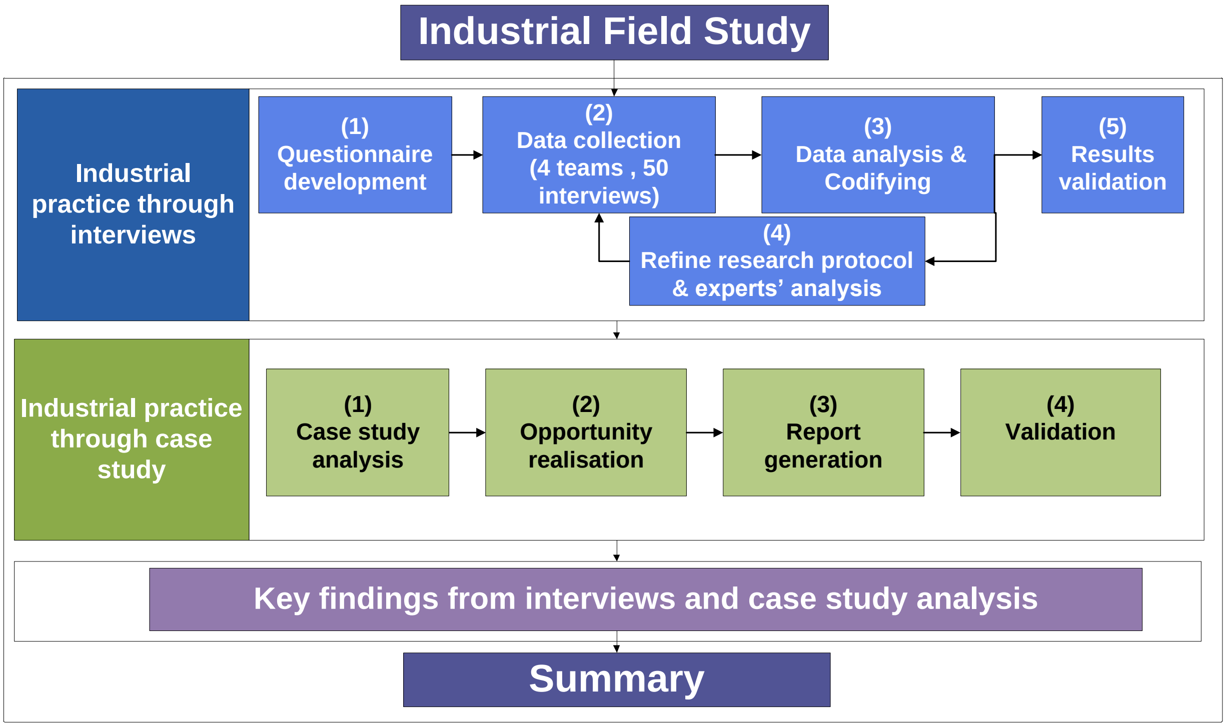


Figure 31: Outline of Chapter 4

The commodity/component repair teams, repair technology teams and engineering to service and design team's senior decision makers were the main group of people for conducting semi-structured interviews.

4.2 Research Methodology for industrial field study

This part mainly served in the identification of the current industry challenges. The structure of the stages is given in the figure 13. The research aim and objectives were used for the development of questionnaires in the stage one. As given in the introduction and methodology, this research opted for formative and exploratory approach. Therefore, it was agreed to use the semi-structured questionnaire due to its flexibility of open and probing questions with clear objectives, which are vital to gain overall understanding of current practises and associated challenges. After thorough scrutiny, the questions of the questionnaire were asked in the interview settings.

The questionnaires were segregated into four segments:

1. Product design &development process
2. Repair design & development process
3. Knowledge-sharing
4. Challenges and key issues

A total of 25 interviews were collected from experts recognised in their role. The specialists selected for interviews were Chief of technology selection, Product development manager, NGV (nozzle guide vanes) repair manager, Repair Casing (Team Leader), Component/commodity Designer and Repair engineer. Table 4 shows an illustration of the experts included in the industrial field study.

The typical interview lasted around 1-1.5 hours, during the first part the aim and objective were discussed after this the questionnaire was completed also recording the open and probing questions and their comprehension before finishing with short term medium and long term future for the repair and design of commodities and components. The responses were recorded and analysed (as described in step 2 & 3 in figure 13) the analysis and codifying of the interview were used for updating the research protocols and followed up (step 4). Lastly, all the analysis and codifying of all interviews were confirmed by the other team members, this was done to keep the consistency in validation.

Table 11: Interviewed professionals

Current Role	Experience (in years)
Chief of technology selection	15
Product development manager	35
NGV (nozzle guide vanes) repair manager	28
Repair Casing (Team Leader)	10
Component/commodity Designer	8
Repair engineer	1

4.2.1 Questionnaire development

Two types of questionnaire were developed, one to focus the aim and objectives for the repair (including but not limited to repair process, optimisation, selection and the challenges in repair) and the second for the design (focusing on the repair knowledge and how design can assist repair in the operational life). Both questionnaires kept evolving as any subsequent interview and questionnaire were updated influenced by previous interviews, input, it also provides higher validity when the design and repair analysis were discussed with teams and other stakeholders.

Understanding of components and repair process in aero engines is illustrated below:

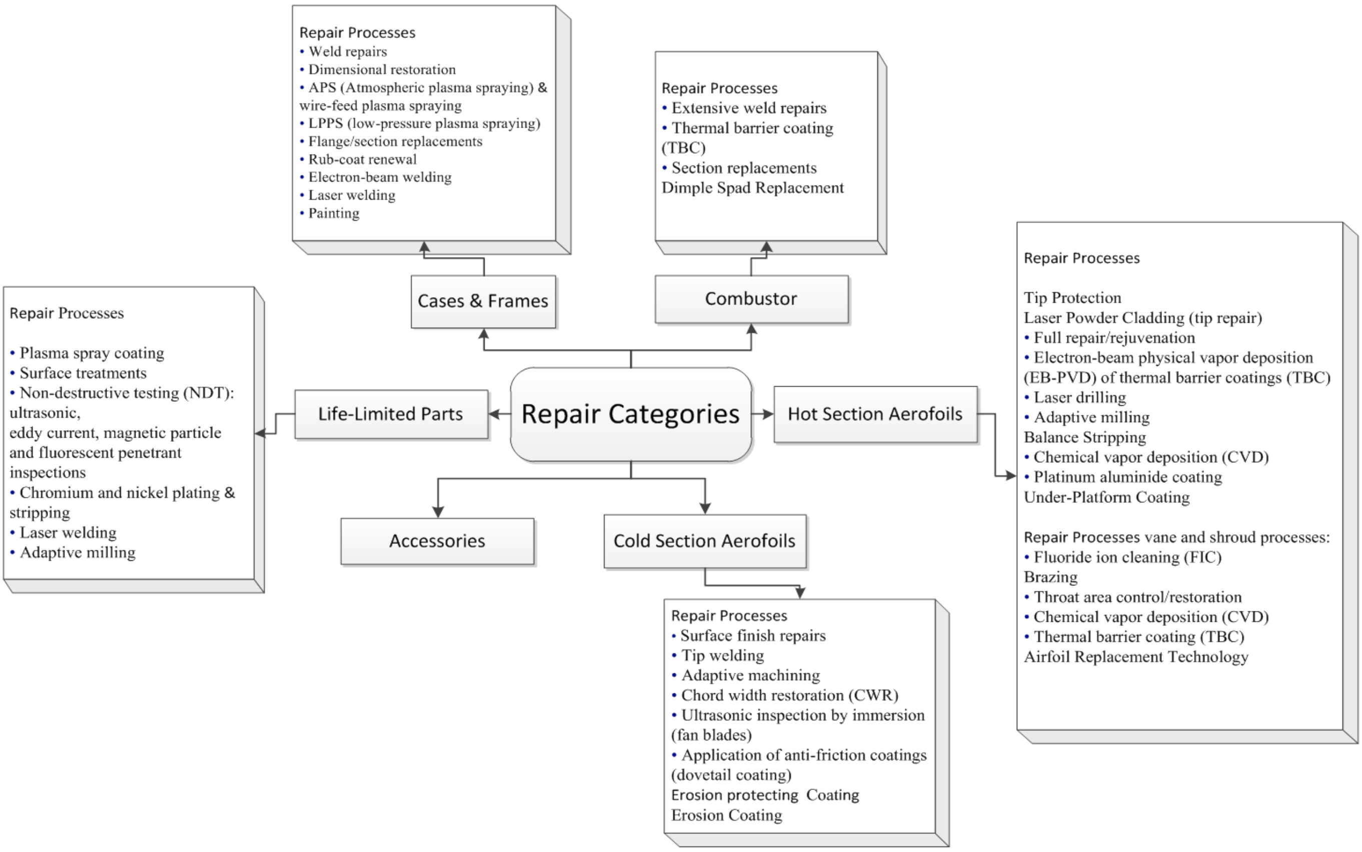


Figure 32: Overview of repair categories and repair processes

The project Zero team carries out the feasibility study for the customer's aim and objectives only from the design aspect. Design and development team develop the design and feasibility for the manufacturing, but the repair feasibility in operational life is rarely carried out.

4.2.2 Interviews and analysis

Critical concerns explored from the questionnaire and interviews

There are many challenges needed to be addressed for effective and efficient repair process selection, some of them are given:

The junior engineer following the best practices, the lack of costing understanding of repair engineers, different repair Processes maturity levels, location based challenges

Technology based challenges and there is no tools are available for effective and efficient repair process/technology selection.

4.3 AS – IS model

4.3.1 Repair strategy

The repair selection strategy in the industry is based on expert knowledge and experiences learnt from the past.

The design develops an anticipated repair scheme of a specific component. The design utilises the available methods of manufacturing processes, once repair process has been matured then the lead repair engineer will update the process to improve efficiency of the repair or if the new repair process needs to be introduced by the approval of the design.

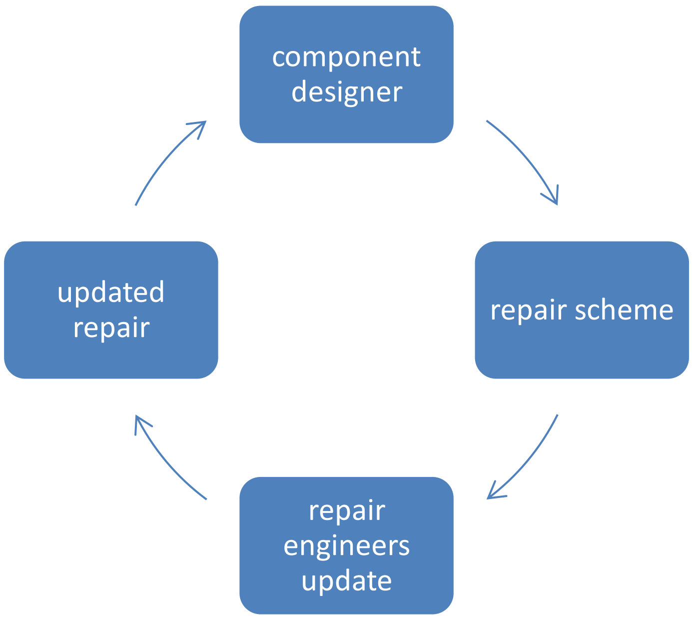


Figure 33 Repair AS IS

A detail survey was conducted from OEMs and MROs companies to identify the repair strategies in aero engine components. The design, manufacturing and repair data were collected across different components.

Based on different components the repair strategies varies significantly, the common categories of aero engine based on parts details is given in the fig.43 repair categories and repair processes.

Whereas Repair prediction models for aero engine uses hot gas path and non-hot gas paths (report GER-3620G), the Rolls Royce take the approach based on commodities

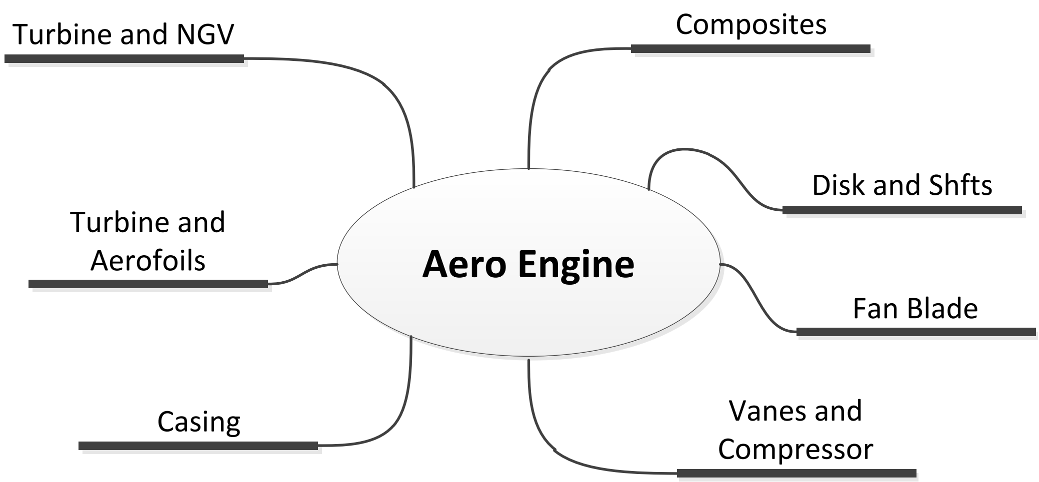


Figure 34: Commodity teams; Community practices (Rolls Royce plc.)

The civil aero industry is now focusing on effectiveness within repair as a further and future part of efficiency drive in the current challenging environment. The recommendation from industry is to develop an effective solution in the large civil aero engine components repair and gathering the repair knowledge feedback designers for future efficient design within repair.

The repair engineers can develop a robust repair strategy which can offer effective and efficient repair. As technologies in manufacturing and repair are increasing an optimised approach to select efficient repair techniques can be selected for aero engine comments repair to gain efficiencies.

The components repair can be divided into different stages, depending on the components and processes used but as a general rule, minimum stages required for repair are not less than three (cleaning, repairing and inspection) and maximum can be limited as 8, each stage a unique process or methods must be carried. From cost effectiveness point of view less stages would be preferred

It is found that there is not a selection strategy in component repair schemes, hence the selection scheme requires are robust and optimised repair selection strategy to be competitive. What are the challenges they are facing in repair optimisation?

Level of transparency in Vendor repair for RR, during repair process negotiation, i.e. how the vendors are repairing different components?

Repair design not optimising manufacturing process routes and not incorporating latest manufacturing technology.

4.4 Case study

Two case studies were piloted during the industrial field study to identify existing practices. The main purpose was to find the components repair procedure and comprehended possible enhancement can be made to make the repair efficient and effective as described in the fig 13.

The case study was for two different components with different damage-modes in tandem, to examine the similarities and anomalies in repair procedures.

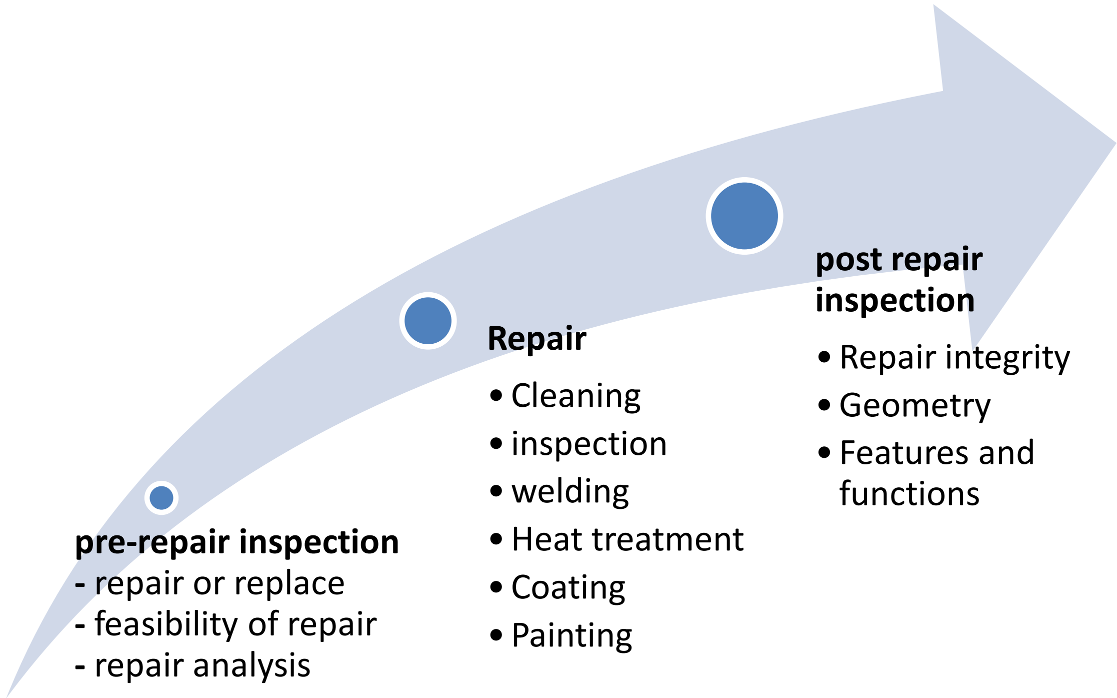


Figure 35 Basic repair procedures

Pre repair inspection

When any component requires repairing, the cost of replacing the component is considered if the cost of the repairing the component is less than 70% (approximately, based on multiple factors) then the component is repaired.

When the decision of repairing is taken, then the feasibility of repair, according to the design parameters are measured.

The repair analysis is the activity where repair processes are selected.

Repair

The repair is a combination of many activities to recapture the life of the component. There are around 5 -7 activates to repair the majority of the components.

Cleaning: cleaning is done to remove contaminants and it is also prerequisites for many repair processes.

Inspection:

It is done to see the extent of the damage; some damages need an extensive inspection like hairline cracks, fatigue initiation, under surface damages.

Welding:

Every repair has its main activity, also referred as a core activity. The welding is very important repair process which is used extensively in repairing many components.

Heat treatment:

After core repair, the function and feature of the component is needed to be according to design parameters, HT is one of the most important parameters of the aero components.

Coating:

The majority of the component has some sort of coating, mainly it is a thermal coating which projects the component of the thermal energy which can compromise the component design integrity.

Painting

Mostly Paints are used to project the component from corrosive environments and surface protection

Post repair inspection

The post inspection is a necessary element of the repair process where the repair is verified.

Repair integrity

The components are measured against the repair processes, whether the repair has been done correctly. Like welding, coating and painting etc.

Geometry

All aviation components have very tight geometry limits therefore the geometry verification is done with great care.

Features and functions

The features and functions of the components are tested before refitting into the engine.

Process selection

The repair process selection is mainly done by repair experts and it is also based on the MRO location's capability and capacity. The most common practices at MRO facilities are to follow the last repair process selection.

The selections of repair processes are not always effective and efficient according to business KPIs and research findings.

The large aero engine component level degradation was also explored so that the repair requirement can be understood and captured.

The large aero engine flight operations are given in the following tables:

Table 12 Aero engine Flight/Hours and overhaul point

Overhaul	Flight	Operation hours (Avg.)	Operation hours (min)	Operation hours (max)	Landing & take-off min	Landing & take-off max	Cruise min	Cruise max
1	3000	38500	20000	57000	0.666666667	1	6	18
2	3000	77000	40000	114000	0.666666667	1	6	18
3	3000	115500	60000	171000	0.666666667	1	6	18
4	3000	154000	80000	228000	0.666666667	1	6	18
5	3000	192500	100000	285000	0.666666667	1	6	18
6	3000	231000	120000	342000	0.666666667	1	6	18

Table 13 Aero engine component degradation at overhauls

Overhauls	Flights	Degradation 1
	0	0.111
1	5000	2
	5000	2
2	10000	8
	10000	8
3	15000	15
	15000	15
4	20000	25
	20000	25
5	25000	50
	25000	50
6	30000	90
	30000	90

Table 14 Aero engine operational Degradation

Overhaul	**Flight**	**Operation hours (Avg.)**	**Degradation (residual) %**	**Increment (residual %)**
1	3000	38500	5%	
2	3000	77000	10%	5%
3	3000	115500	20%	10%
4	3000	154000	40%	20%
5	3000	192500	60%	20%
6	3000	231000	85%	25%

The figure is also given to illustrate components level degradation flight cycle in some case the engines were operating beyond the design limits.

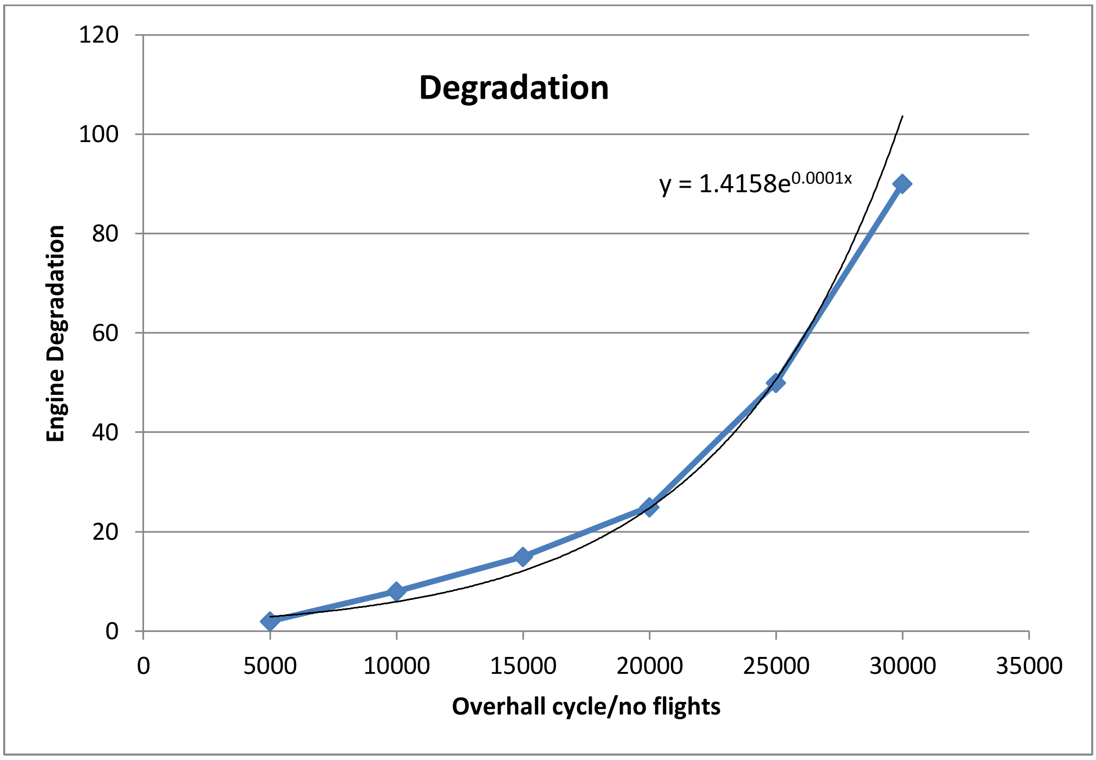


Figure 36: Components level engine degradation (operational)

This research used Pareto analysis to capture the industrial requirements for the selection of the components. Furthermore Pareto analysis also provides assistance for damage mode selection for the selected components. The two aspects, the repair frequencies and repair cost were considered to help of RR expert consultations.

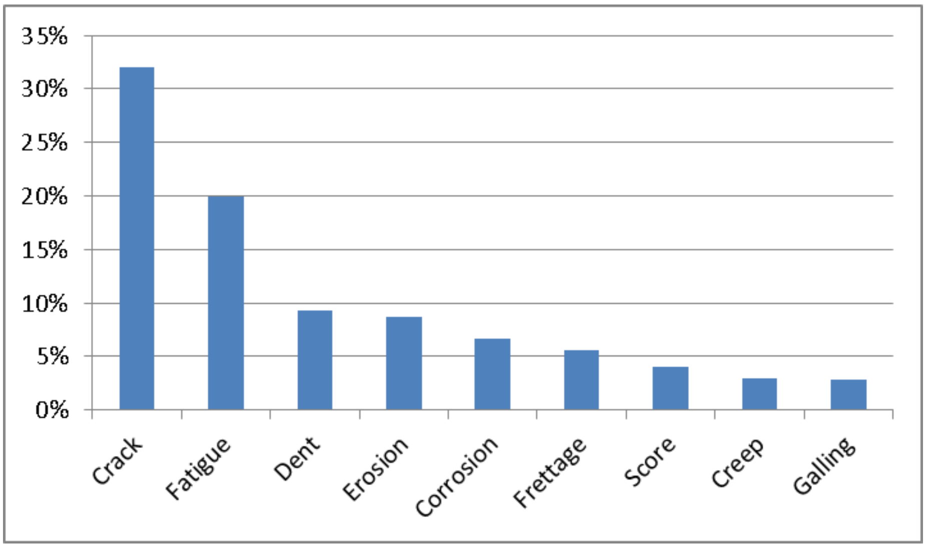


Figure 37 Damage-mode vs. Repair frequencies

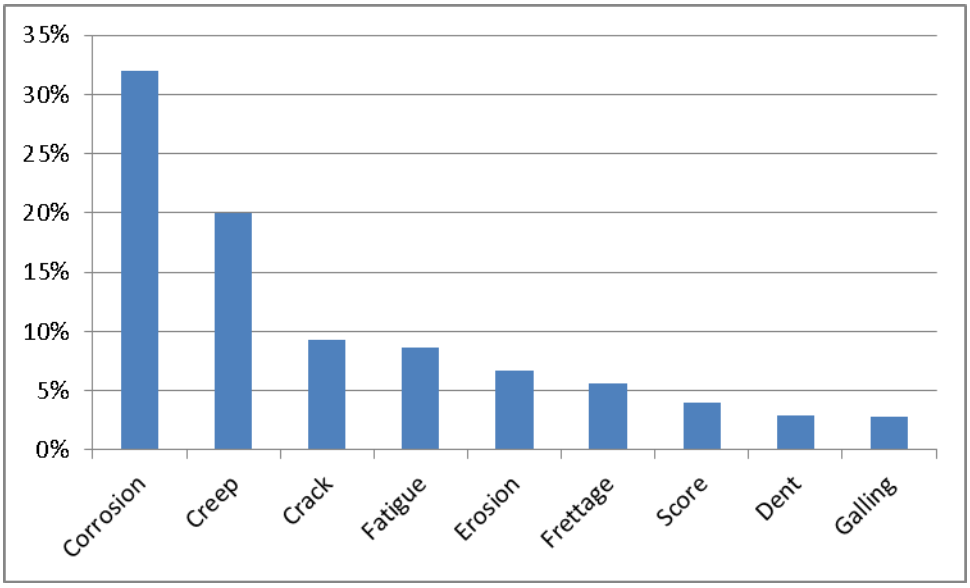


Figure 38: Damage-mode vs. Repair Cost

Two components selected from the data which can consolidate different challenges in one were casing and NGV. These two components were also selected by Rolls Royce experts to examine in more details for the repair process selection. After selecting the component, the common damage modes in these components were studied.

4.4.1 Damage modes of aero engine Components

Aero engine components degrade in operation and develop damage mode, which requires repair over time for safe operations. These damage modes are different and require combinations of repair processes. The damage modes of mechanical components are described in basic physical phenomena. The understandings of damage mode affecting aero engine components are necessary for safe working of the engine. The main focus is on operational damage modes, not accidental or incidental.

The damage modes of the aero engine components are:

- Corrosion
- Creep
- Erosion

- Fretting and Wear
- High cycle fatigue
- Low cycle fatigue
- Mechanical and thermal stresses
- Thermo-mechanical fatigue

Corrosion

Permanent damage caused to aero engine components by corrosive element present in the atmosphere and fuel used as propellant. (E.g. Sulphur, sodium chloride) (2).

Controlling the damage of corrosion has been a big challenge for the industry, but some mitigation includes careful material selection, coating, and careful maintenance.

The corrosion, reduces the operating life of aero engine components by three main mechanisms

Corrosion reduces the mass which affects the surface area and the load bearing area of the component. This weakens the components and fails under normal operating conditions. Large surface areas are easy to identify under inspection but the small area is difficult to uncover but small area corrosion increases the local loading which initiates precipitate component failure under low cycle fatigue or high cycle fatigue. Any failure of such causes cascading effect on other components to fail and degrade.

Corrosion decreases the aerodynamics and thermodynamic efficiencies by affecting the mass and surface area. This makes the surface rough and changes the characteristics of flow not only depleting the efficiency and reducing the engine performance but also increasing the operating temperatures which causes a domino effect on the components and whole engine.

Corrosion also causes blockage of flow due to density changes in the material. In some cases, it can increase the volume by as much as five times, the flow blockage, increase hot spots and leads to premature creep failures

Overall corrosion fails the components, decreases the performance and initiates other failures, some types of corrosion are easy to identify and some kind of corrosion are very difficult to find. Corrosion also make repairs very difficult in some components, especially in complex geometry components, sub-surface and unidentifiable corrosion (e.g. sulfidation). Another phenomenon exist in corrosive environment is called corrosion fatigue. The amalgamation of mechanical stresses in corrosive conditions can fail the component at much lower fatigue cycles, lower loads and in shorter time.

Creep

In stress conditions at higher thermal loads the components undergoes inelastic deformation it is called creep which is time dependent. The higher the thermal loads in stressful environment the faster the deformation occurs. It mainly affects the components in the hotter part of the engine.

Erosion

Erosion is the accumulative deterioration of components which are in the path of fluid resistance (mainly hot/cold airstreams). It is caused by abrasion of hard particle in the passing fluid, over time it erodes the components' shape, geometry and features. The compressors suffer by this damage mode very often.

In the airstream caused by small hard particles carried in the gas path. What differentiates erosion from any other damage mechanism is the scale and nature of each individual damage event. Individually each event is inconsequential in terms of performance loss or reduction in mechanical strength. However, when very many events take place in one particular area of a component, then the performance or strength of that component can be severely compromised. Erosion is often most apparent in compressors, particularly those used in

Erosion depends on the following factors

- Design of the component
- Materials used in the Component
- Operational conditions
- Protective coatings

High cycle fatigue (HCF)

When the component exceeds its material fracture toughness by experiencing the applied stress and crack size is reached in high stress areas, then components is said to be in HFC failure. Crack initiation in HFC is normally time consuming process.

The factors contributing HFC are:

ENGINE CONFIGURATION

INTAKE EFFECTS

OUT OF BALANCE

Low cycle fatigue (LCF)

Cyclic stress with high magnitude has often lower frequency; these stresses get absorbed in the components in the form of strain which will fatigue the components. Due to high magnitude stresses the components spend less time in crack initiations and more time in crack propagation.

Many components in aero engine are exposed to very high loading cycles; hence components' life is limited by LCF.

- The main factors of mechanical loading in aero engine components are:
- Centrifugal forces and thermal loads on the disks
- Torsion and bending forces on the shafts
- High pressures within the casings
- Thermal gradients within components

The recurring frequencies of the forces occur due to the engine vibration often caused by throttling the engine from idle to full to idle. Therefore, the loading cycles are direct effect of throttle motion which causes deviations in rotational speed, thermal distribution in component and engine pressures.

The given S-N curve diagram represents the HFC and LCF failure in mechanical components.

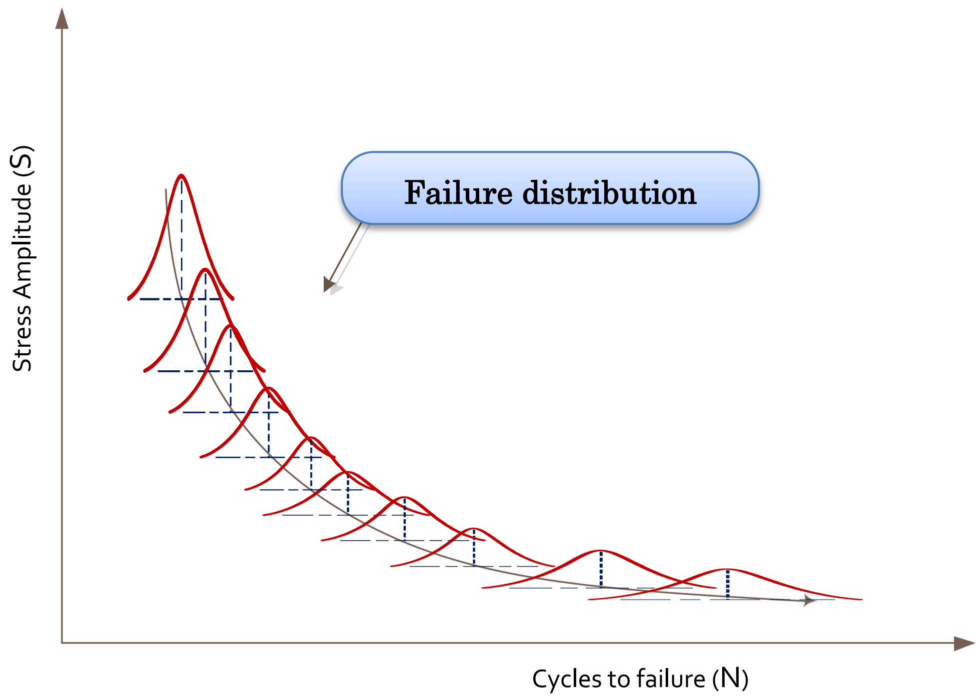


Figure 39: S-N diagram

Wear and Fretting

Wear happens wherever more than two surfaces come in contact, whereas the fretting is the rubbing of two different surfaces with oscillation. It is also notable that the wear is design parameter, but fretting is an incidental parameter of the components.

The main drivers of wear and fretting:

Relative hardness of contacting materials

- Contact force
- Lubrication
- Temperature

External factors

The capacity of a component to defy any damage mode is based on material, design and operating conditions.

In a real sense the design determines the features of the components and its application, hence engine operations and maintenance cannot affect. The engine operating conditions, pattern and frequency of use can be deliberated to be intrinsic factor that has influence on the rate of the component life deterioration. The external influences on the component deterioration are

- Assembly and maintenance errors
- Foreign Object Damage (FOD)
- Limit exceedances
- Material and manufacturing anomalies

The above listed mechanisms are non-operational and non-design and therefore can be preventable, but in reality this is a daunting challenge for the aviation industry

Accurately motoring these damage modes and deterioration of the components has a major effect on the safety of the engine and the operational cost /LCC.

Following are the types of defects are observed in components

Critical component life will be consumed in terms of low cycle fatigue, high cycle fatigue, thermo-mechanical fatigue and creep damage and it is essential to understand how the engine usage relates to the life consumption rate. Significant financial penalties are associated with excessive early retirement of critical components. Conversely, disastrous airworthiness consequences may be associated with late retirement. The situation is further complicated by other damage mechanisms which are common in gas-turbine usage and abusage, such as overseers, corrosion, erosion, fretting, wear and impact damage, and which can reduce material properties and promote early failure of critical components.

4.4.2 Damage mode in typical engine

The real data was covered under the NDA. Hence a desensitise data is presented for illustration

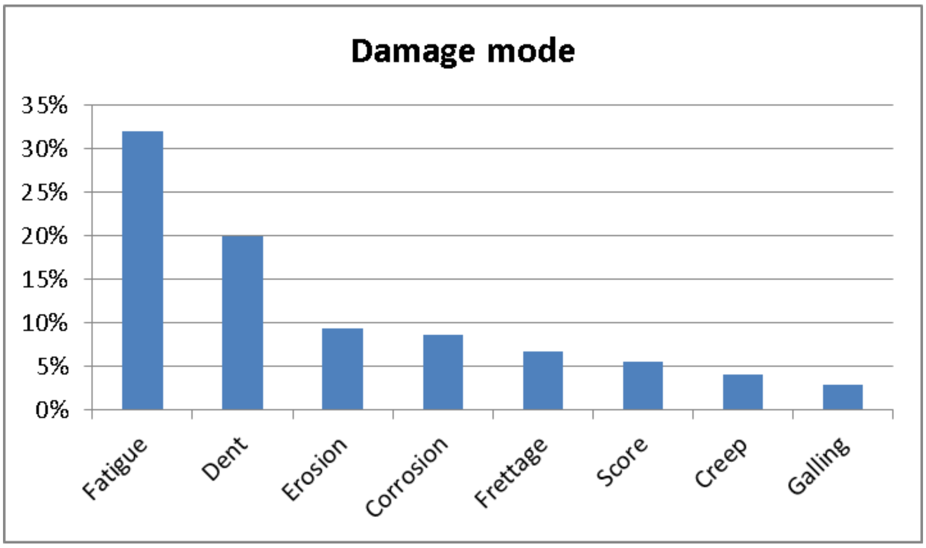
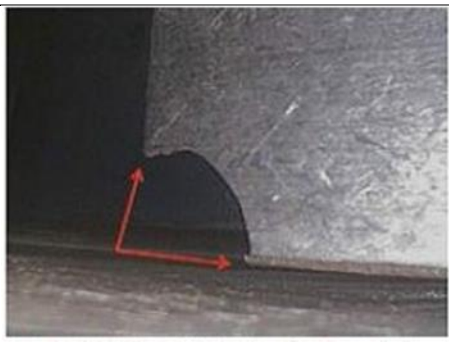
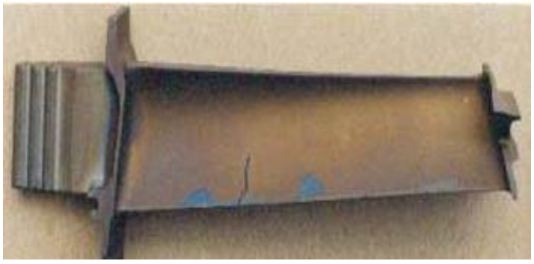


Figure 40 Damage mode of typical aero engine

Table 15 damage modes of components

 Coating Loss	 Tip Damage

 Crack	 Bends, Tear & Dents

4.5 Key Findings from Interviews and Case Study Analysis

The repair and design team concerns and rationales are given in brief:

Repair

- Component Repair decision (repair or replace)
    - The repair decisions are mainly made on the basis of the cost after safety considerations.
    - The subjectivity of repair governs the component repair cost, normally if the cost of repair is less than 65%-75% then it is repaired.
- Traditional approach to repairing
    - There is no repair selection process exists in components repair.
    - No activity based optimisation
    - Mostly, the last repair methods are followed.
- Business team intervention for the improvements
    - If the high cost of repair is analysed by business or cost team, they will prompt and initiate the repair team for the cost control
- The criteria for the repair
    - The main criteria of the repair come from the design specification/repair guidelines
- What design updates can benefit
    - Repeat in design anomalies
    - Design has different understanding and priorities as compared to repair

Design

- Design knowledge sharing
    - The time when components development starts with respect to repair knowledge often it is too little, too late or too much too early
    - The repair feedback becomes ambiguous
- Very little feedback
    - Design has different focus (customer focus, efficiency not repair focus)
    - Design focus manufacturing as more important than repair.
- Repair feedback is not structured
    - Design like to get repair feedback in a structured way with the benefits of the potential updates.

Repairing of aero engine component involves various repair processes, as the technologies are maturing the choices of different repair process become available. As more repair processes are available to MRO facilities, the challenge is to select the effective and efficient repair processes according to business KPIs is becoming more evident. As business cost teams are initiating the repair cost controls.

The repair optimisation (efficiency and effectiveness) is very subjective and not fully understood either. The repair process could be based on activities based repair process, each activity can examine individually assess for the efficiency and effectiveness by experts based on the component and its damage-mode.

Estimation of repair cost is a pre-repair process, not a post-repair process which indicates that the repair teams are less aware of the actual repair cost, making business and cost teams to use a reactive approach to suggest the repair process economy. This reactive approach puts repair team under pressure when the team is not meeting the performance criteria from the start.

There is no tool available for repair process selection; hence the repair team rely on traditional approaches for repair selection which support the hypothesis that there is a strong need to have s system which can select the repair process based on the components and its damage-mode.

There are many instance, were the design updates can reduce the life cycle cost of updating the component design for effective and efficient repair.

Chapter 5

5 Framework for optimised repair selection process

This chapter aims to explain the framework for optimised repair selection process in large civil aero engine component repair which will make the MRO activities efficient, it may also assist aero engine design according to repair. The research scope is on the component level, i.e. engine-shop visit. Hence other maintenances like on wing maintenance and maintenance strategies are not focused.

The aim of the project was to develop optimised repair selection strategy and to develop a repair knowledge sharing to support efficient and effective knowledge sharing at an early stage of aero engine design. As it was very clear that there are two distinctive requirements, one is to facilitate the repair selection strategy and second was the knowledge sharing to design from repair

Objectives were:

When, what and why knowledge needs to be generated to provide meaningful input into the design?

The main requirement of the repair knowledge capture is what information is required in the design which can be benefiting to designers at an early stage. The questionnaire and interview were collected to establish what information is required. The main themes from the data collected, are:

Comprehensive feedback on the reparability of features and functions of the components.

The limitations of the repair processes based on damage modes of the aero engine components.

Recommendations of the updates for the aero engine components.

Identify challenges in aero engine components repair selection techniques and knowledge sharing to designers.

Develop Multi-criteria decision making framework to select repair techniques base on KPIs

Validate repair selection and knowledge framework for appropriate team.

After defining the repair scope, the repair selection strategy can develop. This research can be classified into two major areas

- Optimised Repair selection strategy
- Repair knowledge sharing

The focused objectives provided the main requirements for the project. For the repair team the challenges were often deciding against the conflicting interests for repair selection. So the selecting the key performance indicators as selection criteria was paramount. Another challenge was to select multi criteria decision support mechanism which can provide quantifiable and non-quantifiable selection assistance, because repair team required the selection flexibility of providing quantifiable and non-quantifiable entities.

The main stakeholders in this project were: chief of Repair Technology, Life Cycle Engineering, Repair Engineering teams, and Maintenance team. The requirements are different from team to team, but by keeping the aim and its achievements were deliberated to keep the requirements uniform and within the scope. The mechanical devices for this were the semi-structured interviews with different stakeholders, codifying the interview and draw the requirement and agree on the requirement based on the focus group discussion and meeting with the concerning teams. This process for collecting the requirements supported the inter-team communication and aim in sight.

The transcripts of all interview meeting and discussion were kept for the references propose. Other teams used in this project for expert input are: GRS (Global repair services), repair Technology and Structures and transmissions to independently validate the repair optimisation framework. The group of different people were used to validate the knowledge sharing framework from these teams.

5.1 The Optimised Repair Selection Criteria

The RR teams and focus group from the industry were interviewed for the repair selection criteria, they were agreed as QCD (Quality, Cost and Delivery)

- Quality
- Cost
- Delivery

From the experts focus group it become apparent that QCD (Quality, Cost, Delivery) impacted not only repair or design but many areas as illustrated in the table below.

The standard and common criteria need to develop for repair processes which assess the processes for some given aero engine components. The similar environment was studied which are comparable to repair processes in terms of industry and technology.

The table given also illustrates QCD as the common improvements tools employed in aero and automotive industries. Hence QCD are the unanimously agreed KPIs for this research. Furthermore, the other technical aspect can be sub-part of QCD as discussed later in this chapter.

Table 16 Repair KPIs selection

Improvement tools KPI	Quality	Cost	Delivery	
Lean design	✓	✓	✓	✓
Lean manufacturing	✓	✓	✓	✓
TQM	✓	✓	✓	✓
	✓	✓	✓	✓

The repair process in aero engine components is proving to be a significant part of the repair effectiveness and MRO/maintenance strategy (Rolls Royce 2013)

The repair processes are not directly investigated as a strategic competitiveness or in its own as a field, repair processes get amalgamated between manufacturing processes and maintenance strategies. The newly recognised revenue stream "servitisation" is also proving the importance of repair effectiveness in aero engine OEMs and MROs. (Tim brains 2011), (Rolls Royce 2012)

Any operating system/performing functions to satisfy strategic objectives need to have KPIs as QCD (slack, et. al, 1995. Gunasekaran, et. al, 2001, De Toni & Tonchia 2001). Also significant emphasis was given to process planning. (Shahid 2009)

Common KPIs in different sector:

Table 17 common KPIs in different sector

KPI	Services	Production	Manufacturing	Maintenance
Quality	✓	✓	✓	✓
Cost	✓	✓	✓	✓
Delivery	✓	✓	✓	✓

5.1.1 Quality

Repair, design and maintenance teams of aero engine (gas turbine) has pragmatic understanding of quality which has many dimensions at different levels with varying importance.

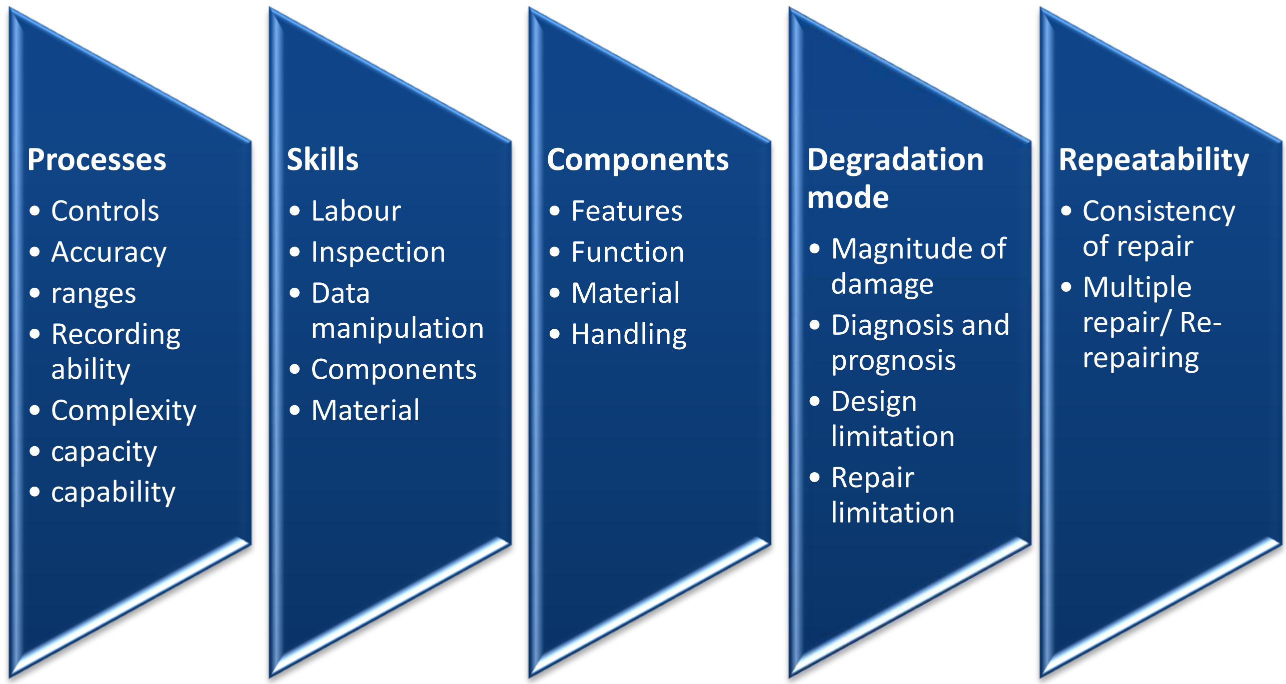


Figure 41quality aspect of repair in aero engine components

The fig 41 provides comprehensive aspect of quality concerns in repair of aero engine components. As a semi-automatic repair framework the repair engineer assesses each aspect of quality before ranking the quality within the ORSS. It is also included in the project scope to have minimum input for the ORSS framework.

5.1.2 Cost

The OEM understanding of repair cost should be based on well-defined structure with all the activities covering the current and possible future cost of repair and the cost of soft issues, skills and strategies required. It also needs to consider the Life cycle feedback from MROs to OEMs on repair strategies, complex decision making and change of techniques and updates carried out. To evaluate the true cost with high level of confidence is difficult (Rolls Royce 2012). There is also a major concern of the repair enabling technologies, some damaged components can be repaired but the inspection technology does not exist. In the case of HP TB (high pressure turbine blade) the sulfidation damage cannot be inspected but some MRO are repairing HPTB without inspecting of sulfidation, the irregularities like this also pose a challenges on repair cost model for aero engine components (GV maintenance team RR 2013).

Repair cost in aero engine is of significant importance to manufacturers and MRO (maintenance repair and overhaul) providers to evaluate the key cost drivers. Cost modelling techniques are used to find cost drivers and also used to find an estimate to the costs incorporated with the repair of particular components or repairing of components by specific process and the economic impact on MROs and manufacturers. These approaches aid the industries to better understand the economic impact of repair technology selection. Understanding the challenges facing the development of a cost model, from accuracy, sources of error and lack of information, provides better risk mitigation and therefore, a more efficient cost model.

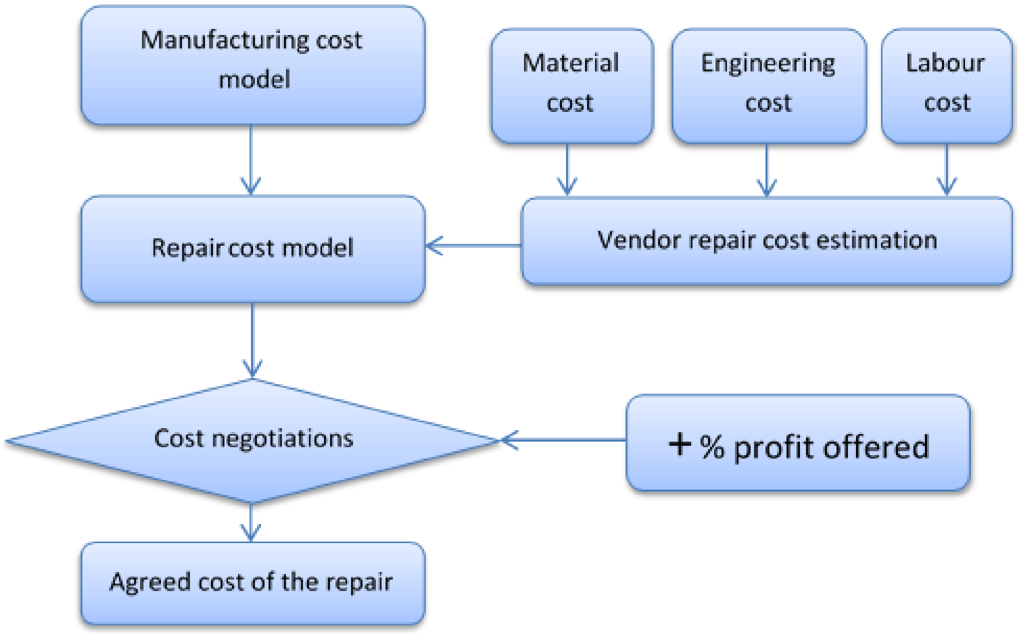


Figure 42 Generic repair cost model

Repair cost model has essentially three parts

Manufacturing cost model of components;

Vendor repair cost estimation for the component

Repair cost Negotiation +agreed offered profit to vendor

The repair staff is very less involved in the costing process therefore it can be said that the accuracy of such model are not as accurate as required due to communication gap and anomalies within the repair process and human factor. Level of transparency in Vendor repair pricing to RR during repair pricing negotiation – i.e. how has the vendor repair price quote been determined?

Repair design not optimising manufacturing process routes and not incorporating latest manufacturing technology.

AS IS model of Aero OEMs

The OEMs current procedure is discussed in more details

Repair cost model of OEMs' is not designed for the repair cost modelling instead it was adapted from manufacturing cost model and LCC (life cycle cost) models. Hence it is a bespoke adoption of different models and refers to many different names and acronyms (e.g. should cost model).

The block diagram illustrates the structure of this cost model.

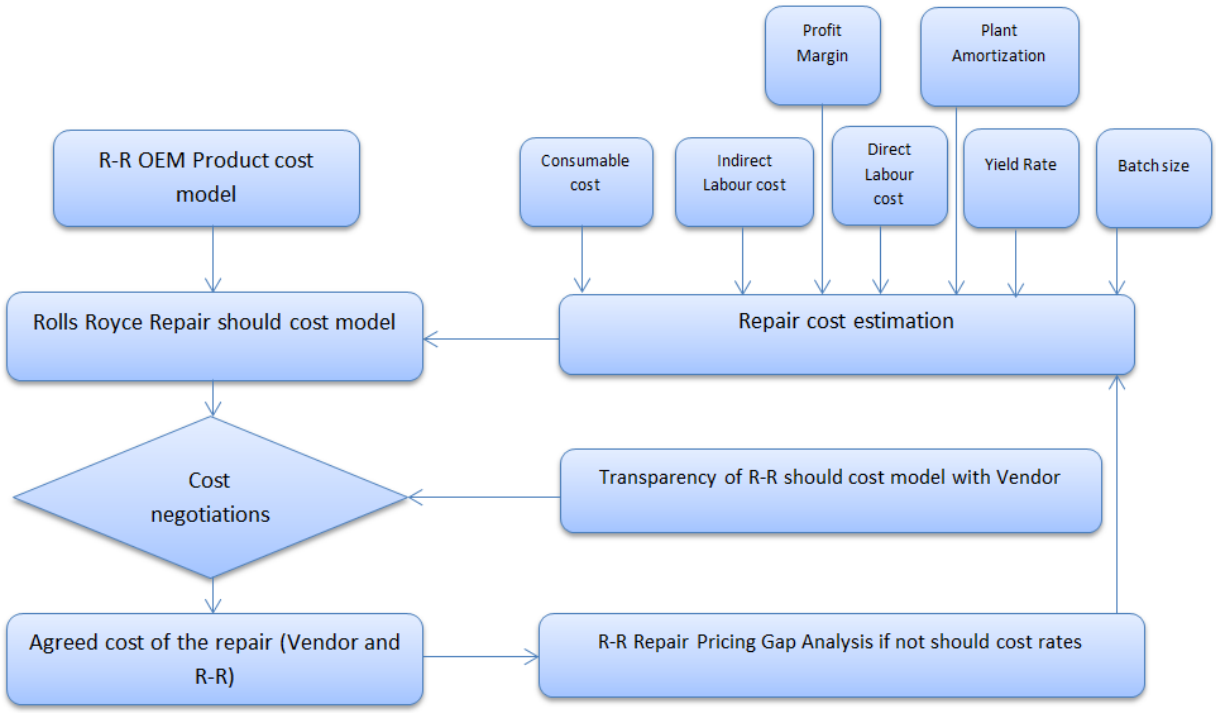


Figure 43 AS IS repair cost model of RR

Challenges:

Cost models are mainly based on assumptions. These assumptions include cost, skills and planning. The limitation is the formal understanding of cost data. (Xue, badawy, baguley, ICMR 2011).

Technical aspect of aerospace components repair cost modelling has many limitations but lot of investment internationally going into MRO mean very stiff competition.

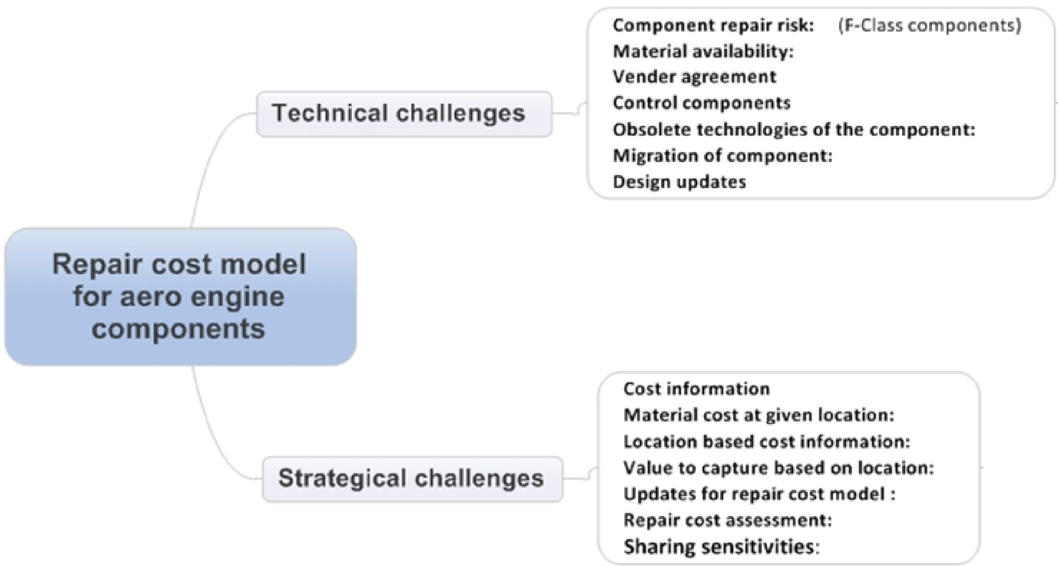


Figure 44 challenges for repair cost model

Technical challenges

Component repair risk: (F-Class components) mainly these components repair has limitation factor of inspection with confidence due to lack of technologies for sulfidation inspection of these components

Material availability: the international availability and legislation of holding material in stocks needs to be addressed thoroughly. The location capacity to repair due to many sourced repair components and sourced repair contacts will also limit the components repair location by OEMs.

Vender agreement: to repair some components is limited to specific vendors which also contribute to the repair costing.

Control components: some components depend on OEM intervention for repair or reuse due to safety, performance and environmental impact required extra activates

Obsolete technologies of the component: Some engines are old as 50-60 year, the component manufacturing is long outdated and the repair is not commercially viable. Limited MRO are offering repair for such components at higher rates that increase the costing challenges for repair of those components.

Migration of component: some of the manufacturing processes is environmentally risky and has lot of legislative requirement, thus has impact on component's costing

Design updates: are also taking place around 3-5 (ref) times in a life time of average component in aerospace for a given asset (ref needed) required the cost model to reconfigure.

Strategic challenges

Cost information: due to competitive pricing the break down details are often not available and some time there is a genuine problem to collection costing data i.e. availability, accuracy, compatibility etc.

Material cost at given location: there is also a challenge of material depending on location.

Location based cost information: the reliability of cost based on the location is another challenge in repair costing.

Value to capture based on location: there is difference in value and its capture

Updates for repair cost model: how to implement new cost model and change managements

Repair cost assessment: the cost drivers are not fixed for the same component, Cost benefit analysis due to different cost driver at each location the analytical data become very limited to location.

Sharing sensitivities: there is also risk of the sensitive information leakage

Significant research has been carried out on working on replace vs. repair cost benefits, however very less emphasis is given to the method of costing a repair. The main cost driver is skilled labour, nearly 35%-40% of the cost is incurred is direct or indirect labour cost. If a given component is repaired 6-14 times in the life of aero engine a significant cost is wasted as a labour cost which is rarely mentioned in repair vs. replacement cost.

Reporting and refining of cost drivers in aerospace components repair needs a lot of attention. There is also lack of information of uncertainty when modelling cost data (Erkoyuncu et. al 2009). Different departments have lack of communication about cost data

As shown in the figure 1 the current repair cost model of RR has many short comings. Some are reported by management as under:

- ✓ They always in need of negotiations for the cost of the repair
- ✓ They need more information about the details of repair costing to be better negotiator therefore more efficient control on repair budgets.
- ✓ Should cost model is somewhat inadequate for the complex components repair.
- ✓ There are also inefficiencies within the vendor repair cost estimations.

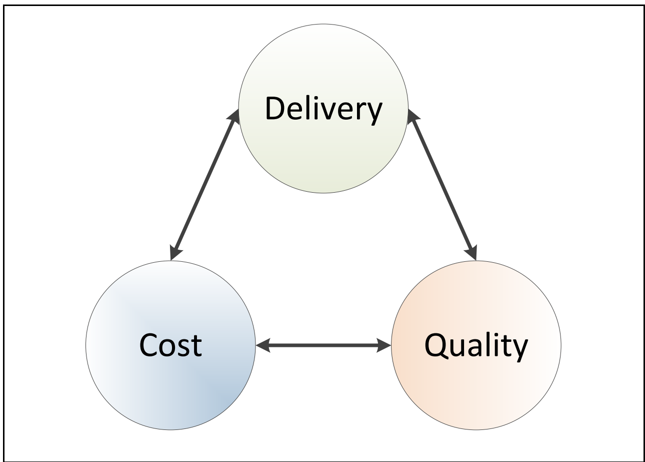
To solve this problem a repair cost model is needed, especially to for the aero engine components repair cost. As, the new processes for inspection and repair are getting discovered and utilised in manufacturing needed to be collected and studied for the benefits and cost effectiveness for the components repair (Xu, Yuchun, et al. 2012). Similar to the manufacturing cost data pool a repair cost data pool can be develop and cross fertilisation for knowledge gains of cost modelling needed to be achieved. Current process of cost modelling is reactive which reports irregularities after they occur. Level of transparency in Vendor repair pricing to RR during repair pricing negotiation – i.e. how has the vendor repair price quote been determined? Repair design not optimising manufacturing process routes and not incorporating latest manufacturing technology.

Rolls Royce repair cost model, Manufacturing cost model, should cost model, Vendor repair cost estimation, material cost, engineering cost, labour cost & other, all attributes towards the total cost of repair. There are very few methods available for estimating with accuracy a compressive repair cost model which can use qualitative data input (Erkoyuncu, John Ahmet, et al., 2013)

5.1.3 Delivery

The delivery aspect of aero engine components repair is unique. Whereas the engine wing-off time is costly and somewhat uniform, the component level repair scheduling is very non-uniform and complex. It is this complex nature of components scheduling makes delivery a unique proposition. Delivery effect the cost and quality in aero engine components repair as illustrated in the figure 46 and 47.

Therefore, QCD is selected as repair process criteria because it proves to be the most common denominator in the technical industries and aero engine OEMs and MROs are recommending these as the best KPIs. The detailed research was also carried out in the bench marking implementation framework in the automotive industry by Baba Md Deros found QCD was industries' recommendations.



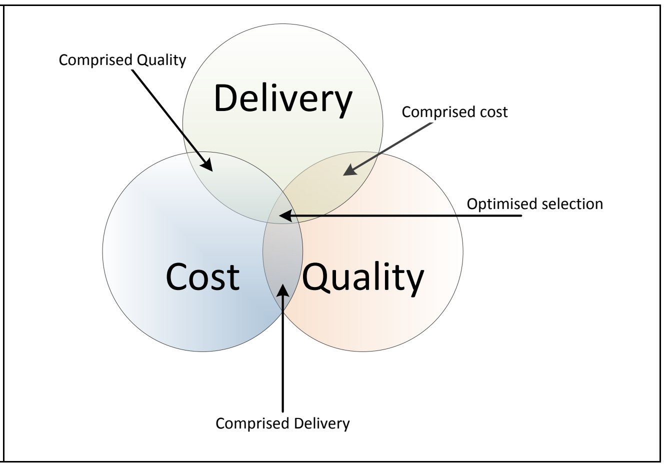


Figure 45: The QCD inter-dependability in repair	Figure 46: The QCD relationship with repair process selection

Venn diagram of the QCD relationship with repair process selection.

5.2 Agreed components

The repair data analysis was done to select the components. The components analysis emerged into the following patterns of the repair within the aero engine repair;

A component which has cost sensitive repair; (these are the component which replacement cost and repair cost are finely balanced)

A component which is based on frequency of repair (these are the components which are repaired more often than other components)

A component which is based on time taken for repair (these components are those which required time intensive repair)

A component which suffering many different damage modes (these components are those which suffer multi-mode degradation)

Single components per engine; these components are those which are high value component and always get repaired for the life of the engine.

The Rolls Royce team wanted to select components which can address most, if not all the challenges faced by different team also conforming to the requirement of the project. From meeting and interview codification the establish criteria were:

The aim of requirement capturing was to examine precise components

In details and its repairing influences, therefore carrying to progress the prominent finding from the interview meeting and data collection. Hence the appropriate components will fulfil the following criteria:

The selected components would be those which are repaired by the Rolls Royce.

The selected components must have a repair teams at Rolls Royce to support.

The components must address quantity and quality issues of the repair. Some components are very expensive and very high value they manufacture one per engine and required to last the engine life with help of repairs.

The components must address quantity and quality issues of the repair. Some components are very expensive and very high value they manufacture one per engine and required to last the engine life with help of repairs. The other kinds of components are low value and high quantity; those are repaired to reduce the extra burden on the manufacturing but needed to be economically focused.

The selected aero engine components which fulfilled the discussed requirements for ORSS (optimised repair selection strategy) were

- Casing
- NGV

5.3 Confirmed damage mode

For capturing the requirements, the industrial stakeholders interviewed were:

Chief of Repair Technology, lead commodity manager from Life Cycle Engineering,

Repair manager from Repair Engineering, commodity maintenance manager from Maintenance.

After data collections on damage mode from design and repair team it becomes clear that design and repair team have many different damage mode focus and some are not common. Observations included that the damage mode effect differently to different components. The selected components damage mode on the basis of frequencies.

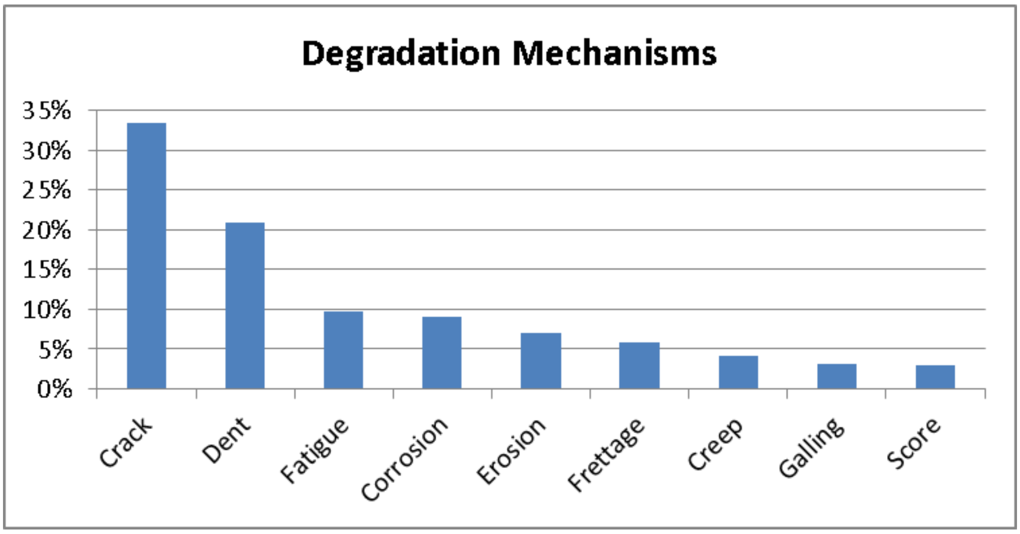


Figure 47: Casing damage mode vs. frequencies

The selected components have also got affected differently to different damage mode as shown in the figure

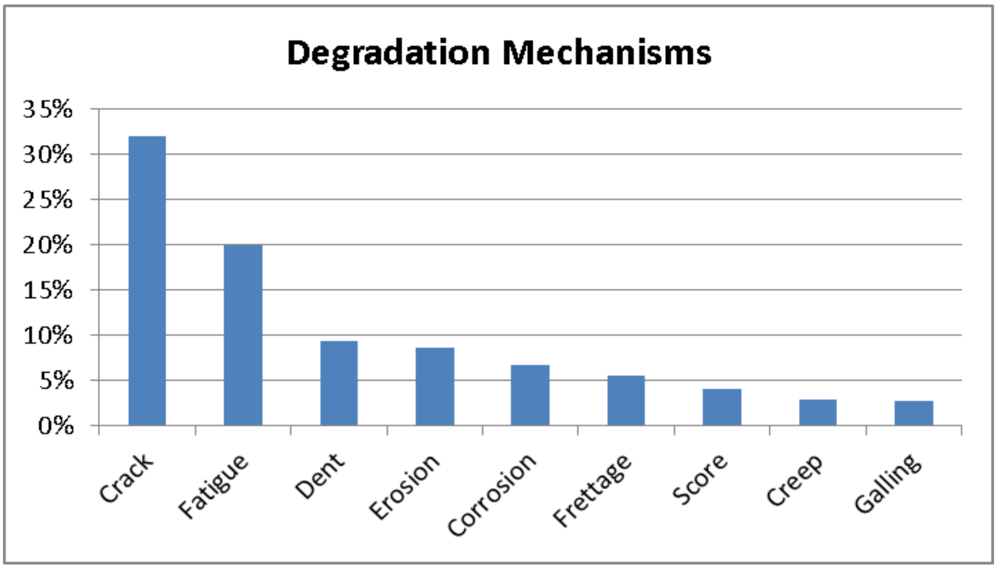


Figure 48: NGV damage mode vs. frequencies

The data also show that the cost aspect of different damage mode based on selected components is also diverse as illustrated in the following figure

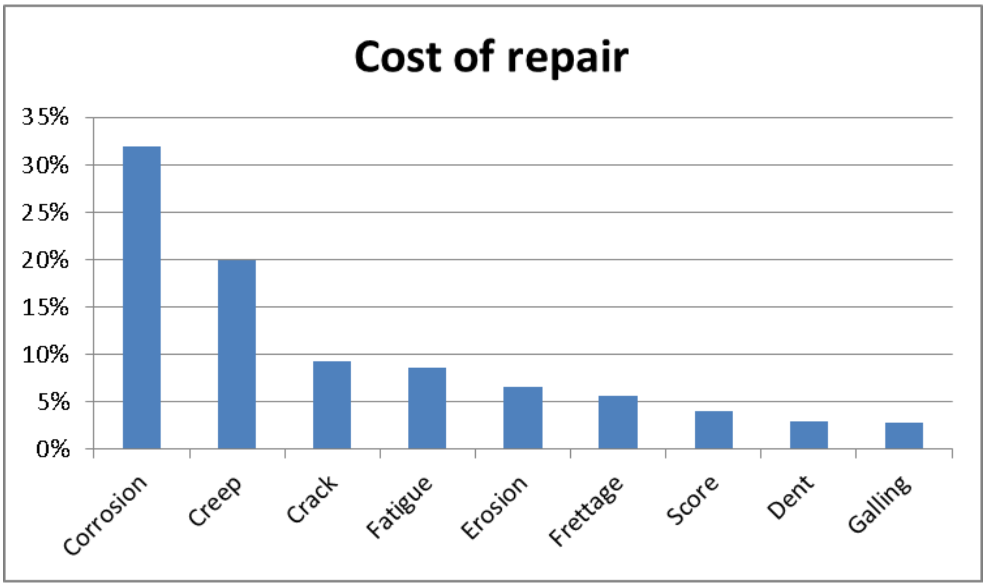


Figure 49: NGV damage mode vs. cost

The repair teams relate different damage mode to different priority which are based on different repair processes.

Damage modes focused by repair teams for casing are given table:

Table 18: Damage-mode focus

Components	Design focused damage modes	Repair focused damage modes
Casing	Cracks	Lining attritions
Casing	Corrosion	Centre aligning
Casing	Erosion	Corrosion
Casing	Galling	Fretting (Wear)
Casing	Creep	Paint damage

The Rolls Royce maintenance team had three predicaments, one the damage mode costing the most in MRO, second damage mode frequencies in the components and third was the damage mode taking the longest to recover in MRO. The selected damage modes were considered on the basis of components' repair expert's preferences, which were indicated by the business data as a main parameter for effective and efficient.

The other aspect emerged was the damage mode of the selected components, it need to be common which exists in many components, not unique which may limit the selection process framework/model and its application. Hence the selected damage modes which are common to many components

The selected damage modes were:

I. Corrosion
II. Cracking
III. Creep
IV. Dent
V. Erosion
VI. Fretting (Wear)
VII. Fatigue
VIII. Galling
IX. Score

5.4 Confirmed repair process

Another aspect of selection was the repair processes. The component selection also emphasised the component selection must be flexible enough to be repaired by many different repair processes, which also lead to repair processes selection addressing the pre and post limitation of the repair processes.

The repair processes were divided into its categories and in the categories, all available process were listed and assessed based on the components and its damage.

The repair processes were divided into sub categories or activities as illustrated below

1) Cleaning
    i) MEK Wipes
    ii) Water Jet

    iii) Chemical dip tanks
2) Painting
    i) Hand Panting (no H/T needed)
    ii) Dip Painting (H/T needed)
    iii) Spray Painting (Can either have no H/T or need an H/T dependent upon specific paint used)
3) Welding
    i) Manual TIG Welding
    ii) Direct Laser Deposition
    iii) Electron Beam Welding
4) Heat Treatment (H/T)
    i) Local Heat Treatment (Blanket in the atmosphere)
    ii) Argon Oven
    iii) Vacuum Furnace
5) Machining
    i) Manual Jig Bore
    ii) Automatic NC Vertical Turret Lathe (VTL) – could have manually turning as an alternative
    iii) Automatic NC Milling
6) Metal Spray
    i) Plasma
    ii) HVOF
    iii) Twin Wire Arc
7) Inspection
    i) CMM
    ii) Hand Tools
    iii) GOM

Development of the Repair Model

Aero engines are multifaceted machines that encompass sophisticated engineering and financial observations. With increasing demands of aero engine in commercial sectors, the OEMs have engaged customers in long-term contracts for MRO. The customers also require efficient and effective relationship from OEMs. Over the years, the OEMs have been subjected to increasing the efficiency and effectiveness of the MRO operations for customers. However, this has become an expensive for OEMs. In order to cut down the expense on maintenance, the OEMs has decided to optimise repair strategy to address this challenge. This approach has presented OEMs the challenges of optimised repair process selection which include repair designs that are exclusively different from manufacturing designs. Business focused, the repair team endorses selection will also be OEMs long term MRO vision.

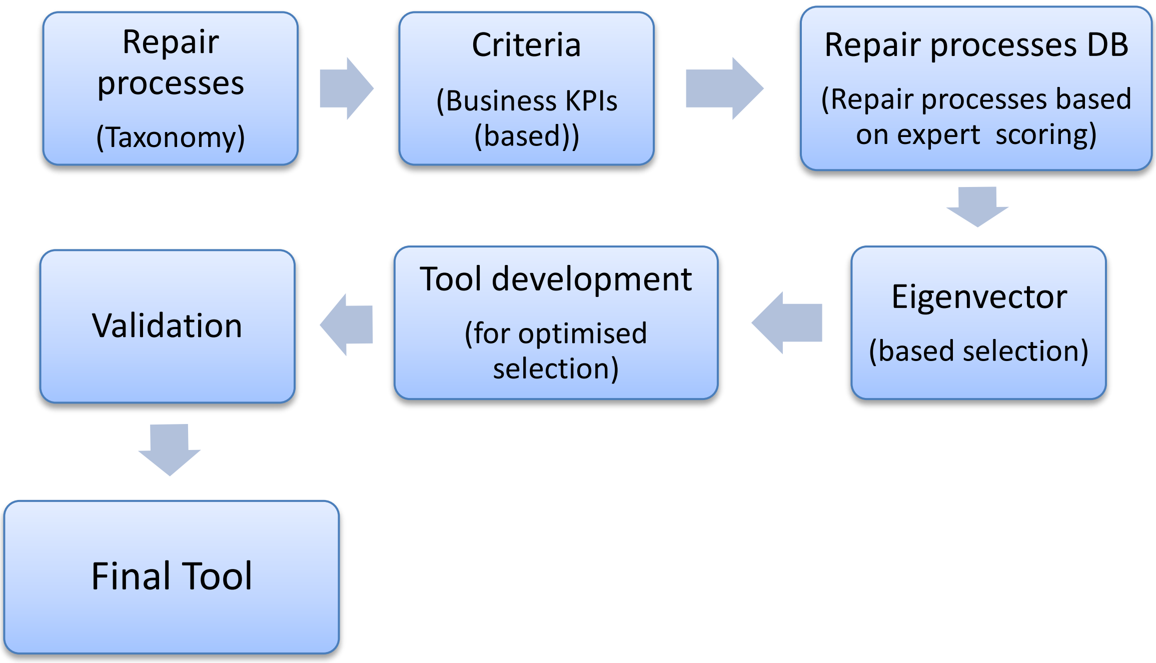


Figure 50 Framework overview

5.5 Optimised Repair strategy selection framework

The framework is based on the matching features required by the repair engineer (quality, cost and delivery) with the processes effectiveness of the component, which are updated by experienced engineer for the given component base on eligible processes. The selected component repair procedure as described can be divided into repair stages, i.e. cleaning, painting, welding, heat-treatment, inspection, etc.

The repair processes are based on the damage mode, i.e. corrosion, erosion, FOD (foreign object damage), cracks, fatigues creep etc. because the repair processes depend on the damage modes.

All the eligible process at each stage is ranked with QCD (quality cost and delivery). The ROP (repair optimised processes) database is created comprising all processes at each stage with a comparative score based on QCD of a given process for a specific damage in a particular component.

A simple demonstrator tool is developed, the selection methodology is based on QCD values of the user, the used defines what QCD values he/she requires for a particular component repair, as QCD values are entered, the tool will give the repair strategy based on input criteria, the tool also provides the 2nd and 3rd best repair strategies.

Two components are used as a case study and validated.

5.5.1 Criteria

For development of the framework, criteria selections are one of the most vital elements. For developing repair selection process out of many. Many maintenance decisions require the evaluation of alternative solutions in terms of complex maintenance criteria such as quality, cost, delivery, reliability and availability requirements etc. Such problems can be formulated as multi-criteria decision-making problems.

It is imperative to decide on how to compare different options which contribute to meet the objectives. This requires the selection of criteria to reflect performance in meeting the objectives. Each criterion must be measurable, in the sense that it must be possible to assess, at least in a qualitative sense. How well a particular option is expected to perform in relation to the criterion. Following are the identified criteria for designing of the repair model. As discussed above that the business KPIs for the repair can be used to select the repair process. The selection criteria are among the most important factors for the framework.

5.5.2 Repair Scheme

Development of repair scheme was the foremost important factor in the proposed model. The criteria, as defined above, served as the baseline for hatching the repair scheme. The fact that component of various other types of engines were being repaired at MRO Factory 'X', was a source of valuable input for identifying the right set of processes to establish a repair mechanism for the rotary component under discussion. The guidelines provided by the manufacturer in terms of technical publications have been yet useful information. The overall mechanism for defining the repair scheme as one of the factors for the overall repair model is shown in the figure given.

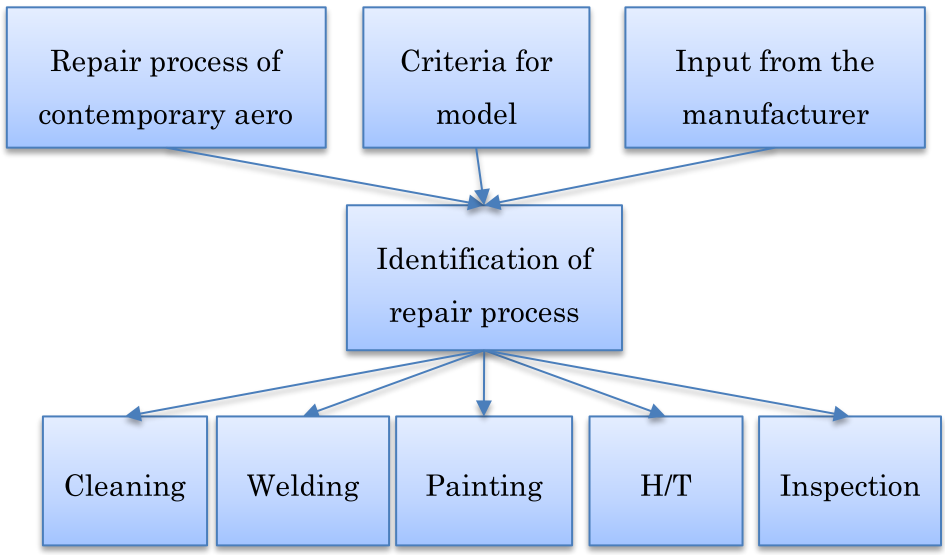


Figure 51 Development of repair scheme

5.5.3 Cleaning Process

The proper cleaning of parts prior to inspection is critical. Successful detection of discontinuities by any inspection method depends upon the effectiveness of the cleaning process. Surface conditions, such as coatings or soil contamination, can reduce the effectiveness of the inspection by interfering with the entry and exit process or producing a high residual background. Inspection is reliable only when the parts to be inspected are free of contaminants. Foreign material, either on the surface or within the discontinuity, can produce erroneous results. Proper cleaning or surface treatment prior to inspection must remove any interfering conditions.

Based on the facts above, cleaning was identified as the second element of the repair scheme.

5.5.4 Repair Process

The repair activates itself in the entire repair scheme is of prime importance. A repair scheme for the component mainly depends upon the type of defect identified during the previous elements of the repair scheme. In case of major defects like breakages, material chipping off and sheering off; the component is rejected and replaced with new ones. However, in case of minor defects; the components are repaired.

The repair can be made up of multiple activities like painting, welding, heat treatment, machining, metal spraying and other related repair activates.

During the course of exploration, repair methods for being followed by MRO Factory 'X' for damaged rotary components were found to be adequate for handling defects of the proposed model. The factory was found to have skilled labour and adequate acumen to handle the defects.

In view of above, repair process came out the obvious activities of the repair scheme.

5.5.5 Inspection Process

The inspection process not only detects the reported defects but it also pinpoints the flaws that are not readily visible while the component is installed on the engine. As per the industrial practice, the inspection process is vital for determining the most appropriate repair procedure for any component. In most of the cases, non-destructive inspections are performed for detection of defects in case of aero engine components.

Availability of available inspection methods within MRO Factory 'X' was significant; hence, the factory facilities were explored in details for all the available options. The factory setup was found adequate to meet the inspection requirement for development of the model.

In view of the importance of inspection for repair and adequacy of the facility at MRO Factory 'X', the inspection process was identified an important element of the repair scheme.

5.5.6 Repair processes database

All repair processes available are included in this taxonomical form for clear identification of the processes. The next step is to develop a component focused QCD (Quality cost and delivery) based database. Where expert assessed scores for each process is ranked based on the components' repair. The score is linear from1 to 5, 5 being the best, efficient and effective. Just to keep in mind that all processes are approved and certified in terms of safety.

The component repair can be split into repair activities and each activity is ranked on QCD based on the specific component.

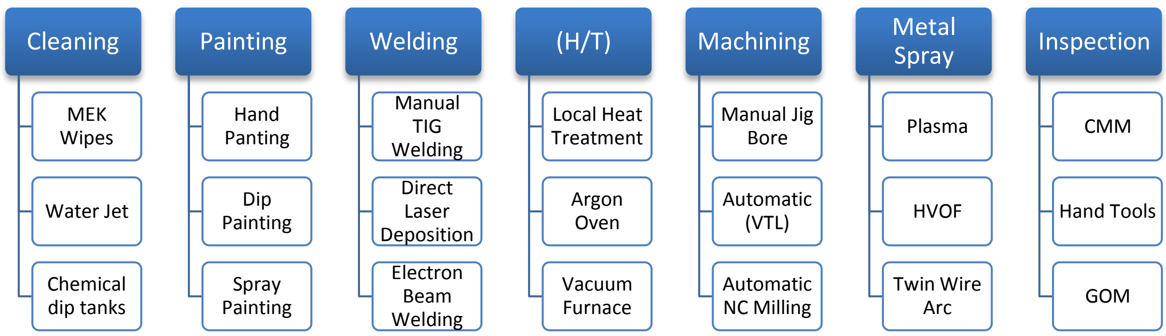


Figure 52 Components Repair process activities

Table 19 Component base QCD score of repair activity of cleaning

Cleaning processes	Quality	Cost	Delivery
MEK wipe	30%	70%	60%
Water Jet	50%	30%	30%
Chemical dip. tank	40%	40%	40%

(Dummy values are used in the table)

The detailed justification of these scores can be further defined on the basis of decision factors based, as mentioned above in QCD.

5.5.7 The Method

The repair process is split into repair activities necessary to complete the component repair, at each activity all the capabilities available process is populated based on the component. First the required QCD to achieve or fulfil the strategic goal or to achieve targets are selected before committing the repair. In each activity the required QCD values are used to prioritise the repair processes based on the components.

5.5.8 Appraisal

At each given activity the repair processes are scored based on the QCD and their sub criteria, the ranking order is formed any multi criteria decision analysis (MCDA) can be used to select the best repair process at the given activity. As a case study AHP is used for the selecting the optimised repair process in the given activity.

5.5.9 AHP based selection

Analytical hierarchical process (AHP) is a process where a problem is broken into hierarchical structured ways to achieve an aim. Since the repair process has already been split into small activities at each activity a process can be evaluated against required QCD and the best can be selected. All the QCD values are based on the pair wise comparison basis.

On the component and processes capacity and capabilities.

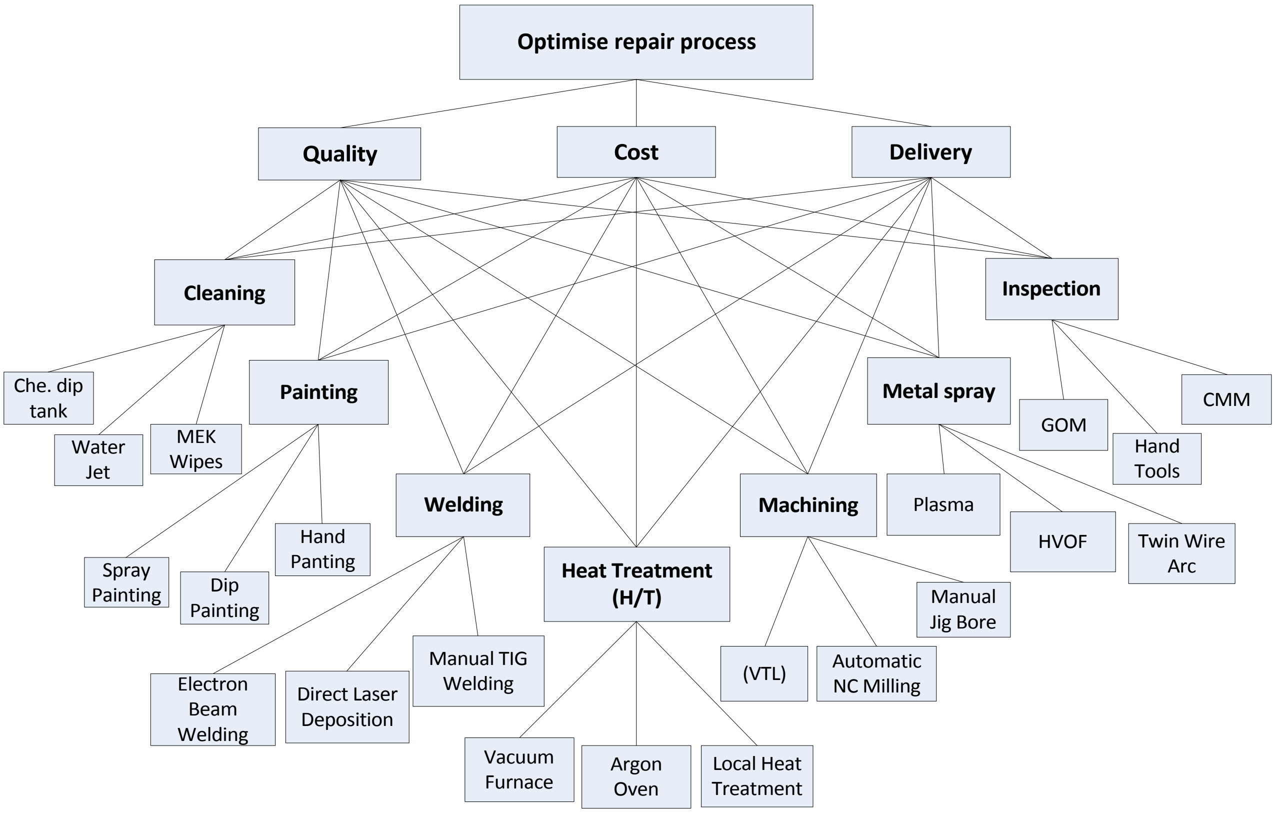


Figure53: AHP selection framework

It is very clear that this technique for repair strategy selection give very informed and focused output. The input of repair engineer is also knowledge for other departments to assess the performance of the processes for the given components and other attributes. These inputs will find the effective and efficient component repair strategy, but with careful analysis the information and the knowledge of the process efficiency of the repair for giving components, i.e. If the process is scoring low how it can be made better (bottlenecks and capacity) also the capability of the process for the damage mode and the components, the limitation can be monitored with the same tool and sharing across different departments

5.6 Functional Requirements

The methods would be able to suggest top three strategies for giving repair for the component. The repair would be split into repair stages /activities which will increase the transparency and future flexibility, also focusing on any given activity to assist decision and selection of individual activity.i.e. increasing throughput capacity or capability.

The main inputs are the QCD based ranking required as a target, what focus is required for the repair based on the business KPIs and the output is the QCD based ranked selection strategy giving the top three repair strategy optimised on given QCD.

5.7 Platform - Usability Requirements

The optimised repair selection strategy tool needs to be developed in MS Excel for demonstration as a proof. Therefore, the techniques can be assessed, how well it is performing.

5.8 ORSS Tool in MS Excel

The model is developed in the MS Excel as a tool for the validity and proof of concept. The use of excel was prescribed in the project scope by the sponsor (RR)

The tool is done on the activity/stages level; each stage is flexible for the inputting of as many as required repair processes/techniques as long as they are in expert database i.e. the repair process/techniques is evaluated against QCD (Quality Cost Delivery).

User can see the output as a whole strategy for repair with each activity/stage with its effective score. There is also a graphical output, which displays how on techniques is better than other so, if two techniques are close to each other semi-automatic decision can be researched.

The MS Excel tool was updated from all the inputs given by RR, each version control works on this basis, i.e. any recommended changes or inputs in the functionality of the tool will be the next version of the pervious. At the moments it is on 11th version

5.8.1 Tool Input parameters

The confirmed parameters for input are QCD of the repair process/techniques and QCD of the required repair strategy.

5.8.2 Tool Output parameters

The confirmed output parameters are stage/activity-wise repair processes/activities based repair strategy with overall QCD scores.

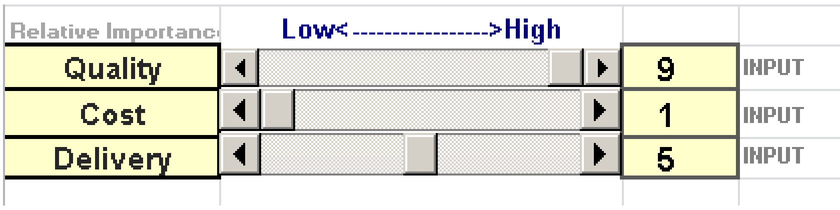


Figure 54 Input of QCD

5.8.3 Tool decision Making Criteria

The decision making criteria is QCD (Quality, Cost and Delivery) agreed as a basis of the performance assessment criteria for the repair team in RR. This common parameter will work in tandem for extracting the efficiency in repair.

MCDA (Multi criteria decision analysis) techniques were exploited and the best serving technique was evaluated as AHP, which is based on the Eigenvector (a mathematical technique which analyses many criteria against the required goal in a structured way), to be used.

5.9 Effectiveness

Effectiveness is the degree to which objectives are achieved and the extent to which targeted problems are solved. In contrast to efficiency, effectiveness is determined without reference to costs and, whereas efficiency means "doing the thing right," effectiveness means "doing the right thing."

This implies that regardless of the economy and man-hours, effectiveness stands out an independent criterion for model development. As the model being developed is for defining a repair process, hence, the effectiveness of the process in terms of technical compliance cannot be over emphasised. No matter how cost effective and less time consuming the process has been designed, it has to be effective so as to bring its practice.

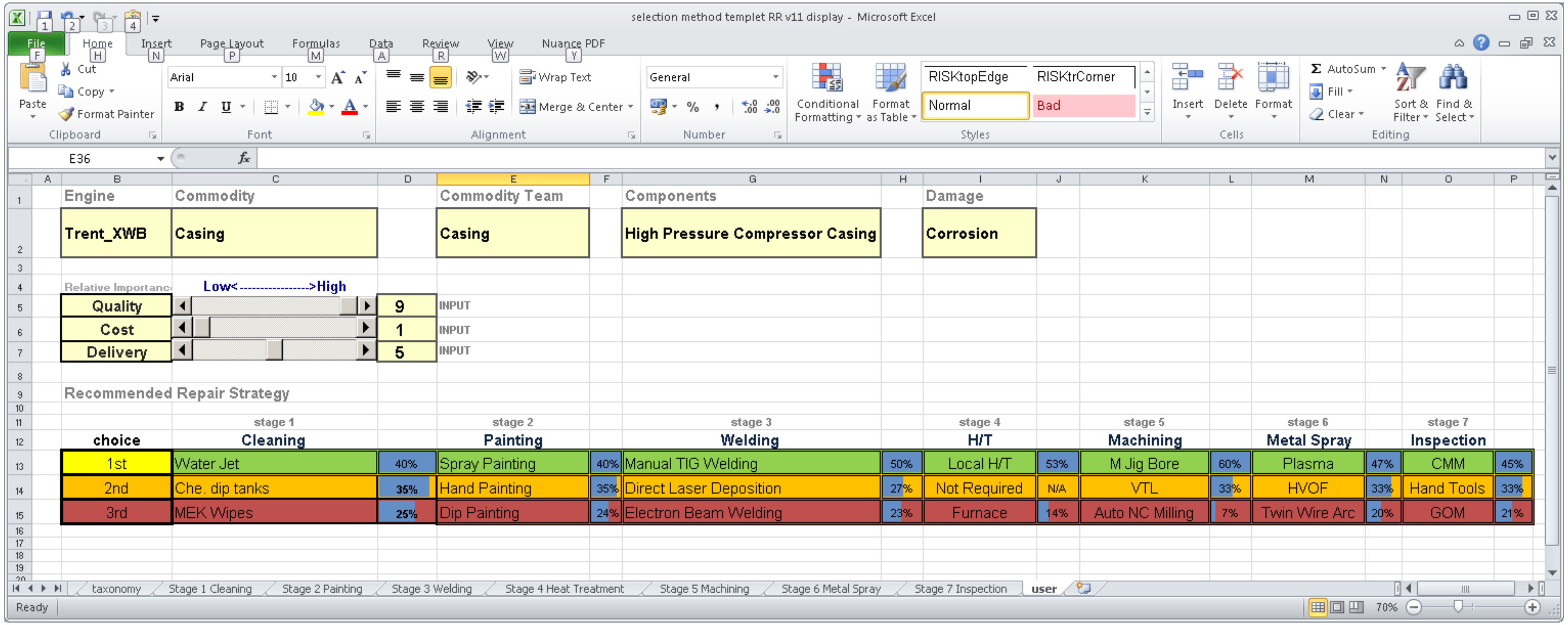


Figure 55 User interface of ORSS Tool

(Figures above and below are given for illustration purposes only, the MS Excel base tool can be seen for the full details and the working of the tool)

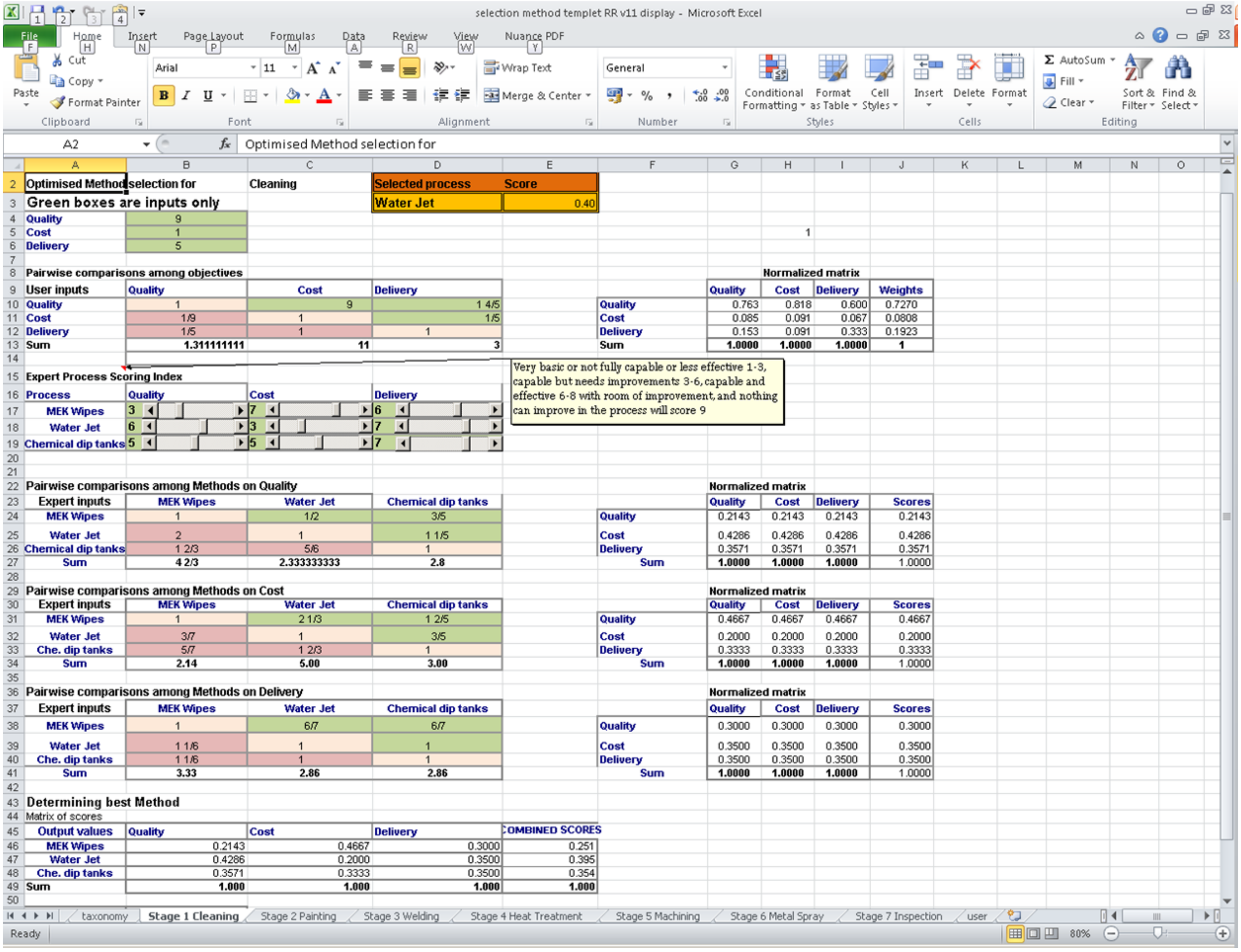


Figure 56 Expert input interface of ORSS Tool database

5.10 The Method

The repair process is split into repair activities necessary to complete the component repair, at each activity all the capabilities available process is populated based on the component. First the required QCD to achieve or fulfil the strategic goal or to achieve targets are selected before committing the repair. In each activity the required QCD values are used to prioritise the repair processes based on the components.

5.10.1 Appraisal

At each given activity the repair processes are scored based on the QCD and their sub criteria, the ranking order is formed any multi criteria decision analysis

(MCDA) can be used to select the best repair process at the given activity. As a case study AHP is used for the selecting the optimised repair process in the given activity.

5.10.2 AHP based selection

Analytical hierarchical process (AHP) is a process where a problem is broken into hierarchical structured ways to achieve an aim. Since the repair process is already being split into small activities at each activity a process can be evaluated against required QCD and the best can be selected. All the QCD values are based on the pair wise comparison basis.

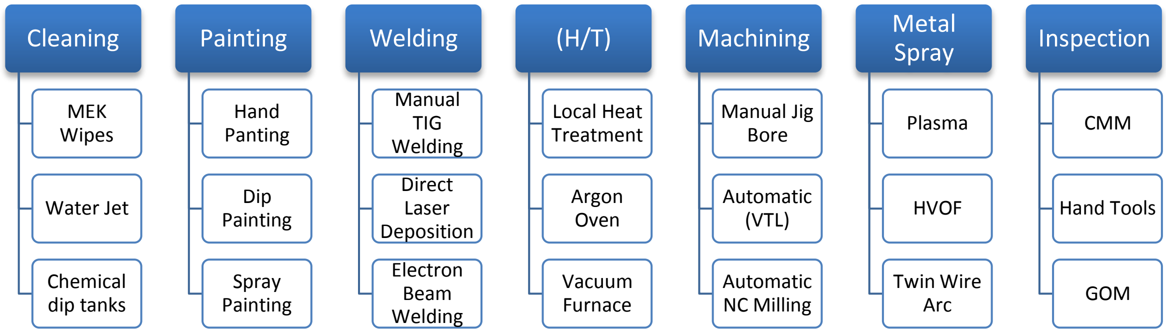


Figure 57: Alternatives pair wise comparisons

The detailed case study is given for illustration.

5.11 Case study

The high pressure compressor case is shown in the figure 3, which requires repair.

Figure 58 High Pressure Compressor Case

The repair process selection tool needs to select the repair process based on the repaired QCD. This casing needs high quality repair and the QCD are mentioned as:

Table 20 Pair-wise comparison of QCD

	Quality	Cost	Delivery
Quality	1	5	3
Cost	1/5	1	3
Delivery	1/5	1/3	1

The QCD scores of each activity in the HPC case

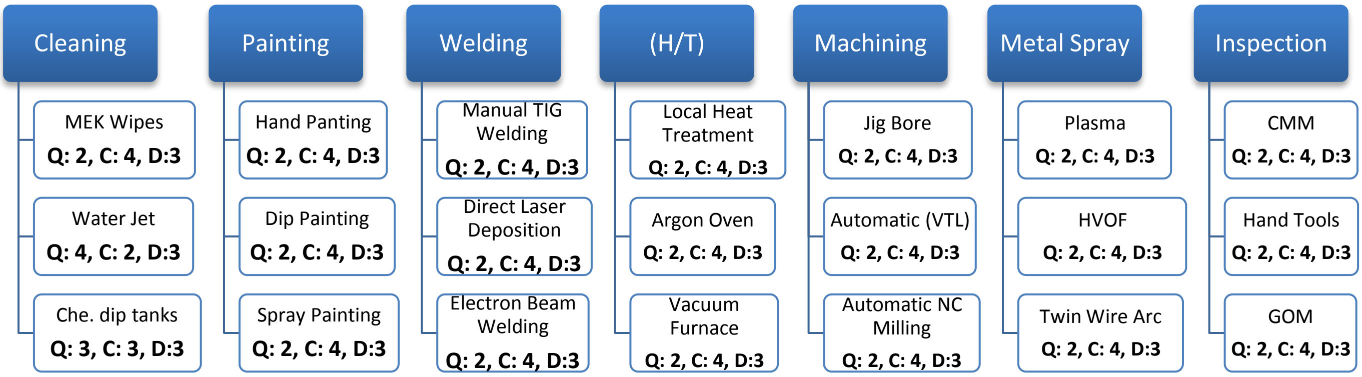
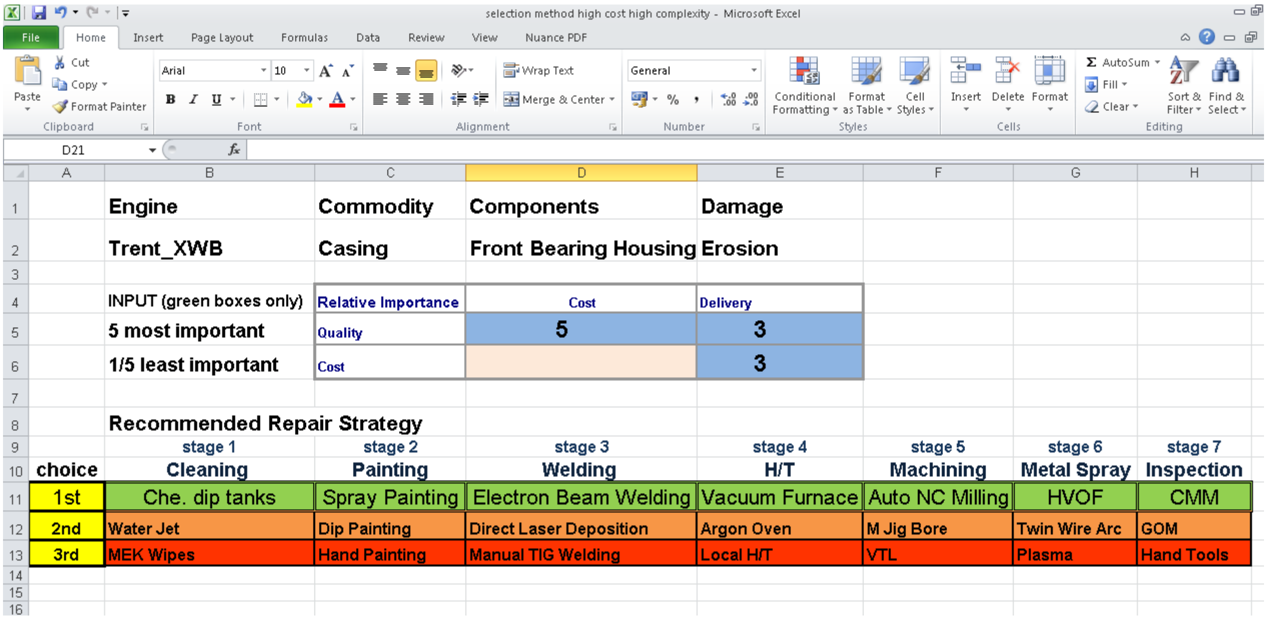


Figure 59: Pair-wise comparison of QCD

The AHP tool was designed to work out the best method for each activity for the selected QCD

The output of the tool:



	Engine	Commodity	Components	Damage			
	Trent_XWB	Casing	Front Bearing Housing	Erosion			
	INPUT (green boxes only)	Relative Importance	Cost	Delivery			
	5 most important	Quality	5	3			
	1/5 least important	Cost		3			
	Recommended Repair Strategy						
	stage 1	stage 2	stage 3	stage 4	stage 5	stage 6	stage 7
choice	Cleaning	Painting	Welding	H/T	Machining	Metal Spray	Inspection
1st	Che. dip tanks	Spray Painting	Electron Beam Welding	Vacuum Furnace	Auto NC Milling	HVOF	CMM
2nd	Water Jet	Dip Painting	Direct Laser Deposition	Argon Oven	M Jig Bore	Twin Wire Arc	GOM
3rd	MEK Wipes	Hand Painting	Manual TIG Welding	Local H/T	VTL	Plasma	Hand Tools

Figure 60: Repair selection tool outputs

The tool recommended the repair activity at each stage of the repair; this selection was validated from the industry's repair expert in aerospace turbine engine OEMs and MROs

5.12 Operational Repair effectiveness and efficiency

There is no comprehensive definition or understanding of repair efficiency and effectiveness. Due to subjective understanding, it is difficult to quantify the repair of mechanical system or mechanical components (Haynsworth, H. C., & Lyons, R. T. (1987) and (Steinhilper, R. 1998). The operational efficiency and effectiveness of repair is different because business assessment of repair is based on KPIs and selected as performance targets. The repairing of components is comparative and very subjective, due to its subjectivity it is very difficult to measure and mostly overlooked. It needs to be explained in repair cohesive manner. The repair is linked with degradation/deteriorations. The industrial field study was carried out to examine this distinctiveness.

From the industrial case study of the selected components, simply degradation paths can be classified into two categories. These are: 1- Linear degradation and 2- Exponential Degradation.

5.12.1 Linear Degradation

This scenario applies when the cumulative damage has not substantial effect on the rate of degradation. Wear of brake pads/clutch can be modelled linearly where the brake pad thickness reduction rate is linear. A general model for linear degradation paths are shown in Eq. 1.

$$S(t_i) = \emptyset + \beta t_i + \varepsilon(t_i) \qquad (1)$$

Where:

t_i : Time index

$S(t_i)$: Measurement signal

$\emptyset$: Deterministic parameter

β : Stochastic parameter

$\varepsilon(t_i)$: White noise, $N(0, \sigma^2)$

Deterministic parameter $\emptyset$ is application dependent and assumed to be zero when the equipment is healthy. Figure 61 depicts five linear degradation path signals obtained using Eq. 1. All signals are initiated with zero degradation level and propagated until they reach 100% damage severity.

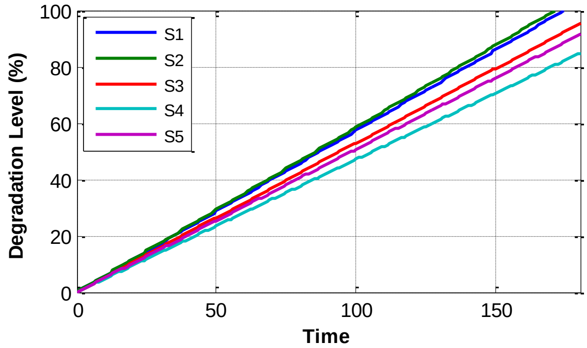


Figure 61 Linear degradation

5.12.2 Exponential Degradation

Unlike linear degradation scenarios, exponential degradation scenarios embrace the applications where cumulative damage plays a significant role. Like most mechanical degradation profiles, bearing degradation, crack propagation, or deterioration in civil structures and processes involving corrosion follow exponential degradation path (Gebraeel, N., Elwany, A., and Pan, J. (2009) . Exponential degradation general form can be explained as Eq. 2.

$$S(t_i) = \emptyset e^{(\beta t_i + \varepsilon(t_i) - \frac{\sigma^2}{2})} \qquad (2)$$

Where:

t_i : Time index

$S(t_i)$: Measurement signal

$\emptyset$: Deterministic parameter

β : Stochastic parameter

$\varepsilon(t_i)$: White noise, $N(0, \sigma^2)$

Figure 62 shows exponential degradation signals created using Eq.2. Fixed parameter $\emptyset$ chosen arbitrarily as 0.67. Mean and standard deviation attributes of the stochastic parameter β is chosen as 1 and 0.1 respectively. Not surprisingly, the variance in degradation level among the signals increases when it nears to the final stages which reflect the real life degradation variance phenomena.

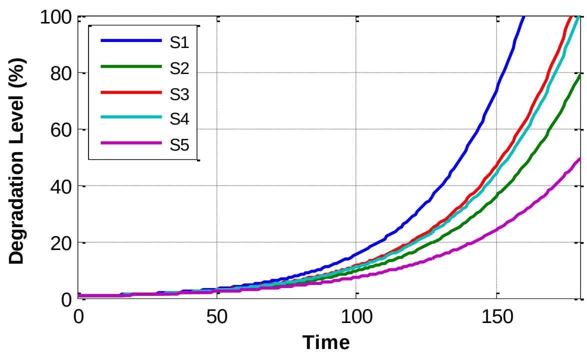


Figure 62: Exponential degradation

The NGV and casing were the selected components which followed the exponential degradation. NGV degradation data was modelled to describe the repair efficiency and effectiveness Degradation of the NGV was divided into three steps. In first phase the NGV degradation was assessed, where no repair were offered, in second phase NGV degraded but subjected to repair and in third phase NGV degraded but subjected to the best repair. The best repair processes was assessed by NGV repair experts.

Table 21: Guide Vane degradation data according to performance

Flights	Degradation (no repair)	Degradation (with repair)	Degradation (with effective repair)
0	0.111	0.111	0.111
5000	2	2	2
5000	2	1	1
10000	8	8	8
10000	8	5	3
15000	15	15	12
15000	15	10	8
20000	25	25	22
20000	25	15	12
25000	50	50	45
25000	50	35	28
30000	90	90	70
30000	90	75	65

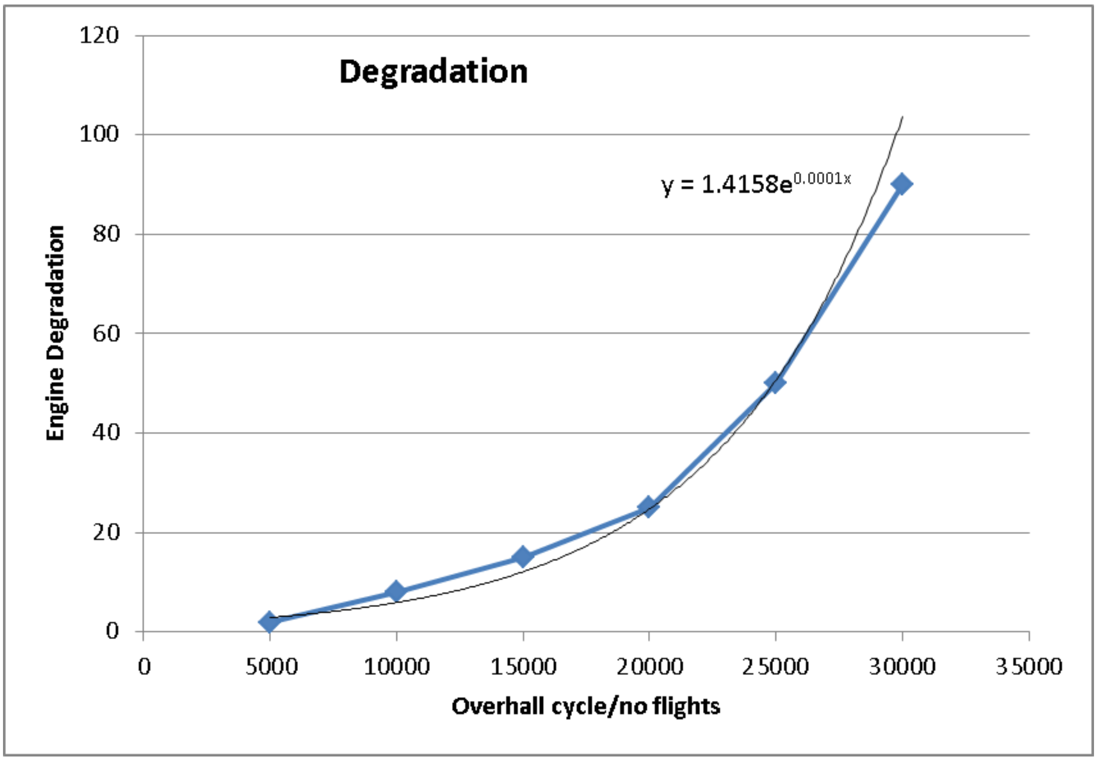


Figure 63: NGV Performance Degradation

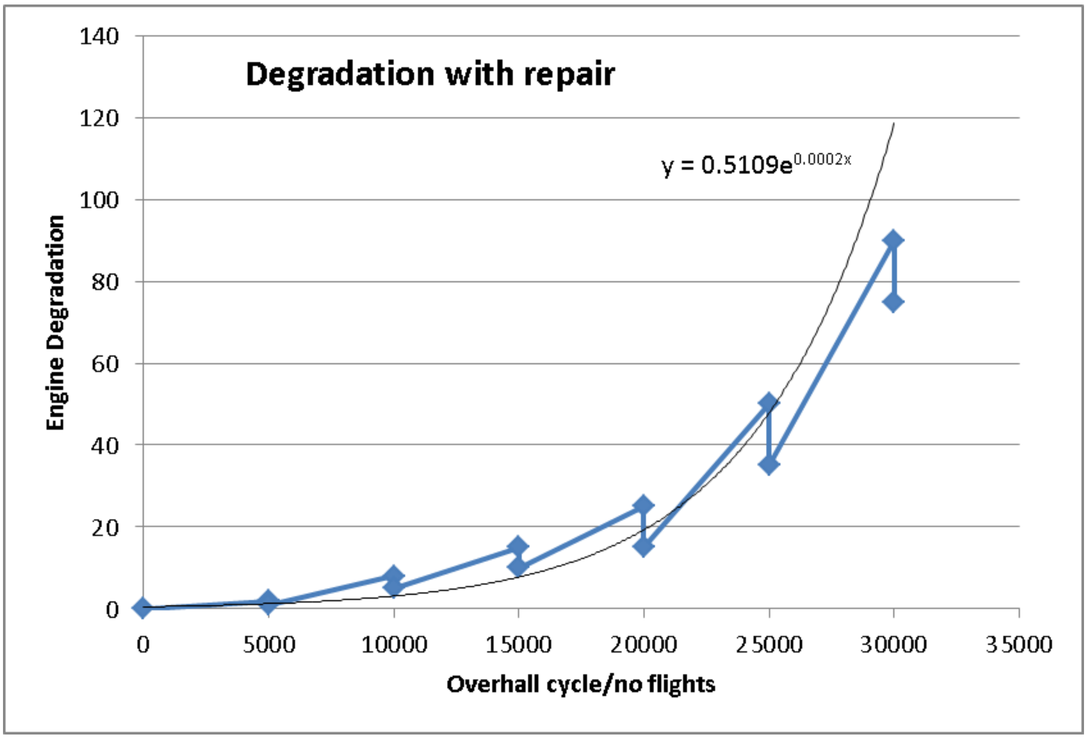


Figure 64: NGV Performance Degradation (with repair)

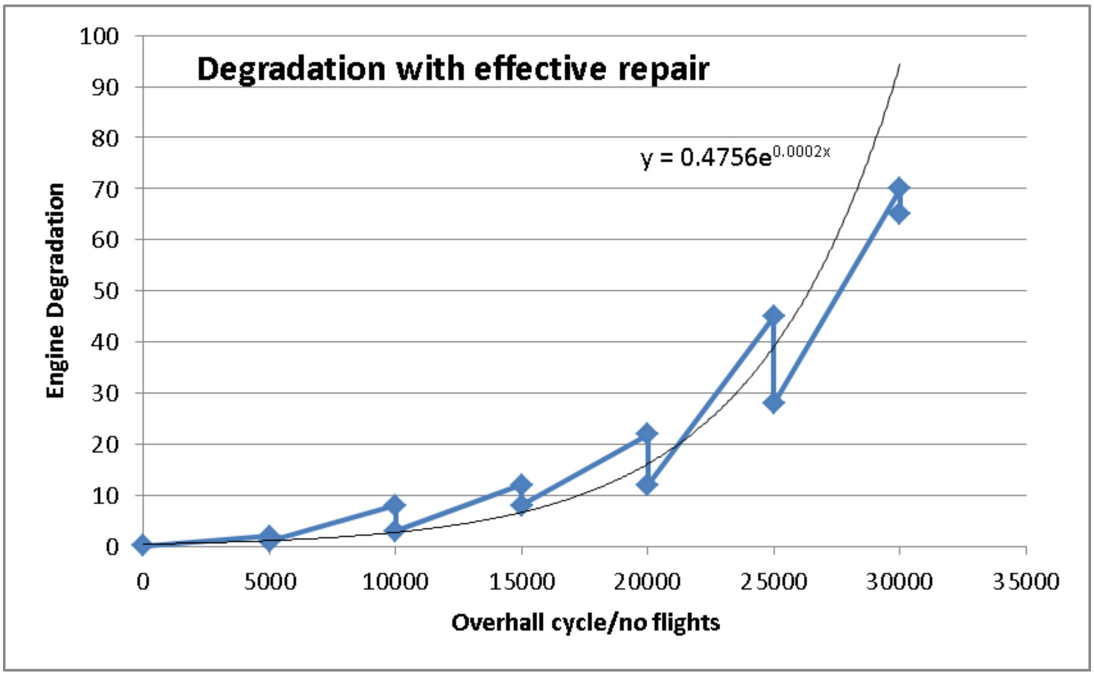


Figure 65: NGV Performance Degradation (with effective repair)

5.12.3 Analysis

The analysis of the parameters of repair, remanufacturing and manufacturing with respect to efficiency and effectiveness are conducted. These parameters will support the measuring the effectiveness and efficiency of repair in mechanical systems.

5.12.4 Repair

The function of repair is to bring the component/mechanical system back to its operational condition, whereas remanufacturing brings the component/mechanical system back to its new condition (Johnson, M. R. & McCarthy I. P. 2014).

5.12.5 Manufacturing

Manufacturing is the original activity to convert the design into a product with the design specification, where the focus is to produce the product in most economical and efficient way (Unit, E. I. 2010). The manufacturing cost plays an important role when deciding the repairing of any mechanical system/component.

Measuring of manufacturing productivity is based on real value added per hour, which can be describe as a measure of manufacturing as whole which varies vastly country to country (Baily, M. N., et. al, 1995)

The manufacturing efficiency is not completely defined; it can be linked with the cost Efficiency, Flexibility, and Market-Based Performance (Swink, M., et. al, 2005). Hence main parameters for manufacturing is based on processes flexibility and cost efficiency. The manufacturing cost has become the reference point to assess the repair or replacement of the component/mechanical systems.

In aviation, most of the components are designed and manufactured with specific amount of useful life mostly defined in hours of operations or service life. The operational/service life degrades as mentioned in degradation model in 2.2. As the life degrades the performance of the component/mechanical system also degrades normally proportional to its remaining useful life.

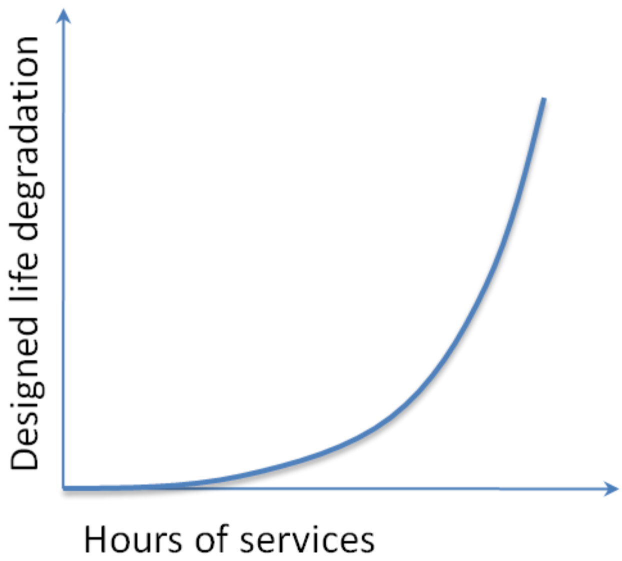


Figure 66: Performance degradation of service life

5.12.6 Remanufacturing

Remanufacturing is relatively new approach to address the environments and manufacturing costs. The focus of the remanufacturing is to take used components/mechanical systems and make it like a new same as manufacturing but with lower costs. Lot of manufacturing organisations are investing in setting up a remanufacturing as a result (Zhang, X., et al,. 2015). In essence remanufacturing is recycling the component/mechanical system to its new state with less cost than its original cost of manufacturing.

Cost of manufacturing = cost of remanufacturing + x (where x is gain in economic efficiency).

Therefore it can be said that the parameters for remanufacturing is economic efficiency compare to manufacturing and the effective selection of the processes to achieve it

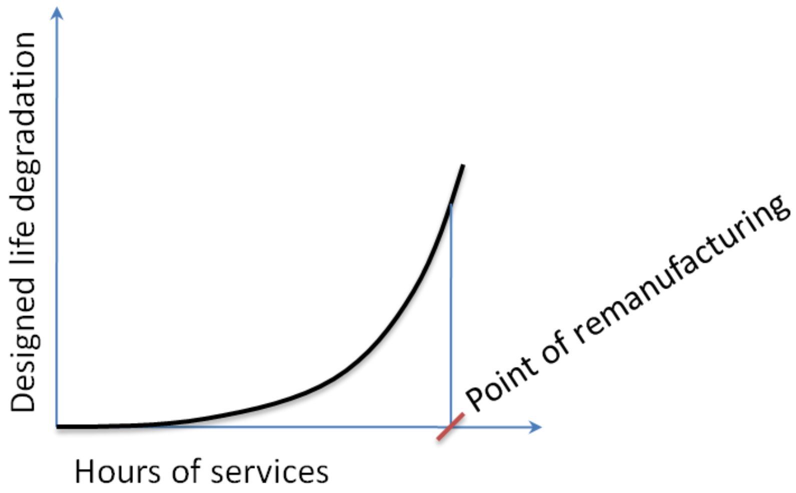


Figure 67 Illustration of Remanufacturing

5.12.7 Repair Efficiency

The repair efficiency is based on the cost of repair, as most of the repair decisions are made on the basis of comparative cost of manufacturing. (Justin, C. Y., & Mavris, D. N. 2015) The main challenge is to define the operational subjectivity of the repair with compare to recapture remaining useful life (RUL) of the component/mechanical system.

The repair efficiency can be express similar to mechanical efficiency as:

$$\text{mechanical efficiency} = \frac{\text{measured performance}}{\text{ideal performance}}$$

$$\text{Repair efficiency} = \frac{\text{recapturing cost of RUL}}{\text{manufacturing cost}} \; (cost\ of manufactirng > \ cost\ of\ repair\ )$$

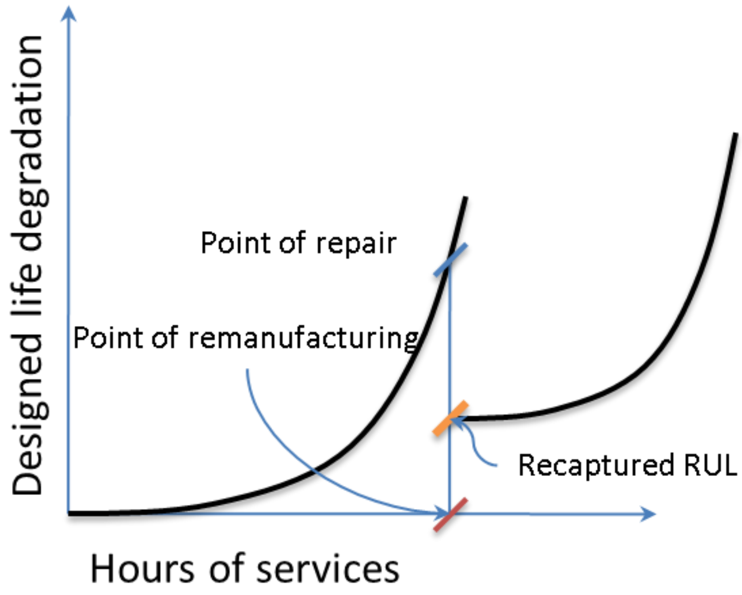


Figure 68: Illustration of repair and remanufacturing difference

5.12.8 Repair Effectiveness

the repair effectiveness depends on two factor, one how much of RUL is captured and second how consecutive repair are benefited, because some repair processes may hinder the repair flexibility, as flexibility is an important criteria.

$$\text{Repair effectiveness} = \frac{\text{recaptured}\ \ \text{RUL}\ (new\ life)}{\text{Design life}}$$

The recapture of remaining useful life is very subjective; often the repair does not consider the cost vs. RUL. The cost comparisons are mainly done from the cost of manufacturing rather than the cost of remanufacturing. The repair team always considers the manufacturing cost before repairing but should consider remanufacturing cost.

Chapter 6

6 Repair knowledge sharing framework

6.1 Introduction

The data collection and industrial requirements presented earlier provide the main requirements for the repair knowledge sharing at early design stage. The collected data provided summary of the hypothetical framework, finding the repair knowledge sharing needs, underling the necessary elements of the framework, including explicit and tacit parts for the repair knowledge sharing processes under evolution. Furthermore, the data collection also provided the acquisition of repair knowledge sharing for specific components at early design stage. These results emphasised the inputs of domains specialist (repair experts, process experts, maintenances experts and design experts) to effectively share the knowledge requirements. The main focus was the available repair knowledge sharing to design at an early stage; some initial challenges were presented in the diagram 69.

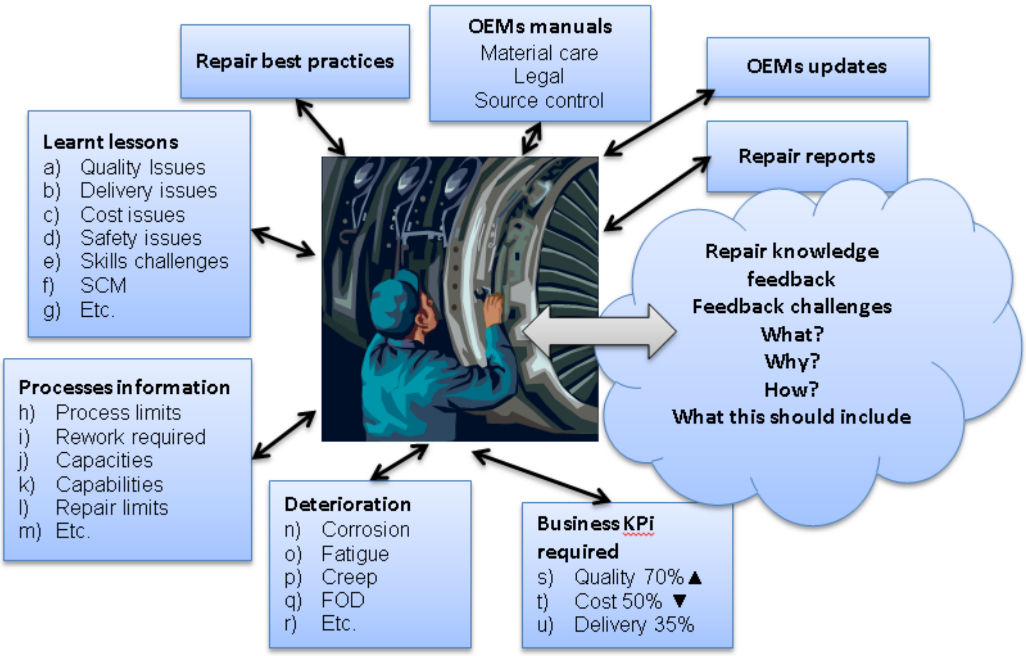


Figure 69 Repair engineer feedback challenge

This chapter combines the results by data collected and considers how it can be used for effective repair knowledge sharing, therefore delivering the research objectives of repair knowledge feedback. A systemic structured framework is developed to be used at the operational level by designers and repair engineers to share repair knowledge at early design stage. Hence the aim of this chapter is to discuss the proposed a framework to provide repair knowledge to design team, i.e. Repair knowledge sharing from the repair teams to design teams to assist them in early design stage for the aero engine components.

6.2 Framework requirements

The aim of this framework is to assist the design during the early design stage by facilitating the repair knowledge so the design can address the repair issues during the operational life of the engine. A key challenge is to identify the repair knowledge that needs to be generated to provide meaningful input to the design team. The challenge is the represent all the knowledge in such a way to aero engine component designer for meaningful updates in forthcoming aero engine components.

In repair domain, the repair engineers are overloaded with the information from many different sources often conflicting and they are challenged to select the effective feedback to design as shown in the figure 69.

The repair engineer uses his expert judgment to make his/her most decisions, among other task repair engineers are now required to give feedback to design engineer task as well.

The elements of the framework are gathered from the requirements for the design and repair.

The key requirements of the framework are as under:

- What repair knowledge feedback is provided?
- What features and functions are repair of components.
- What are the repair processes used to repair these features and functions?

- What damages are experienced by these components?
- What are the ideal repair processes for these components?
- What design update can be made to make repair efficient and effective
- Why design update is beneficial

These elements of the framework were acquired to achieve these requirements:

- ❖ Cohesive understanding between Repair and design for the repair feedback
- ❖ What aspect of design updates will be beneficial to repair?
- ❖ Why these updates are necessary?

The repair domain needs to be understood more comprehensively to achieve the above requirements.

What is the component level repair of the engine? Component level repair of aero engine means, it is off the wing and on the MRO/OEM site for repair, as illustrated in the fig below:

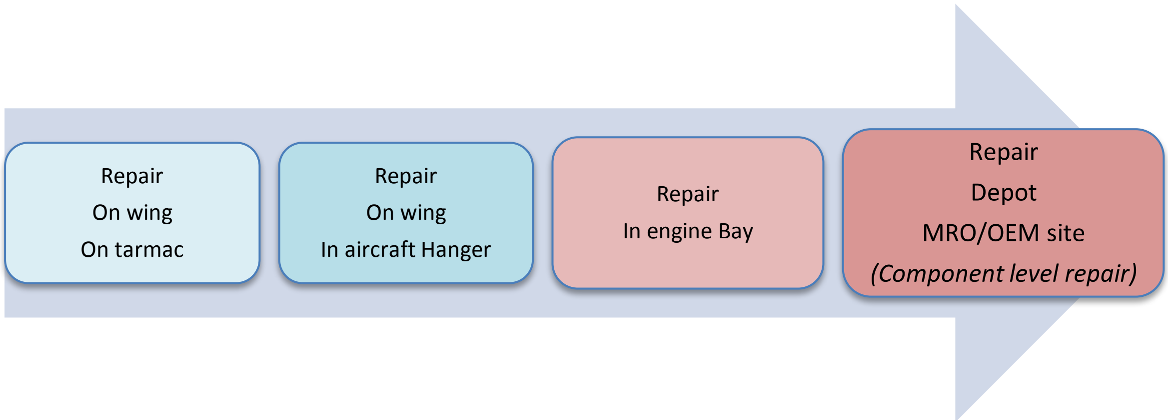


Figure 70 Components level repair

6.3 Motivation for framework

Knowledge sharing to design can solve many challenges for repair engineers. Among many other advantages it will support repair engineer in effective decision making and will reduce the work load repair processes that can be managed more effectively and efficiently, further efficacy captures.

Early interviews from the repair team, which included chief from Repair Technology, Graeme Donaldson from Maintenance (NGV team), manager from

Repair, Engineering (casing) and lead commodity from Life Cycle Engineering established that repair knowledge sharing will provide effective, better future planning with the effective selection of repair processes, the knowledge base for training and repair analysis for technology selection. The improved future design of repair feedback to designer and Design for Reparability in components.

To resolve these challenges and provide effective solution for the design feedback the repair feedback initiator, would offer:

- A knowledge structure for repair feedback to designer
- Multi domain Repair expertise
- Adaptable strategy with repair lead and developer control
- Input from repair at each stage and mitigation
- Repair processes QCD assessment
- Design update recommendations
- Components Feedback reports, including benefits
- Design updates tracking

The prerequisites are from the inputs are collected from a series of interviews and feedback from experts in the field of components design and repair team of aero engine OEM. The approach can be utilized by many different users from different industries. The demonstrator was developed for the proof of concept. The components repair knowledge sharing will/may grow exponentially due number of components, repair processes involved in it and the complexity of the components, also the need to update will be very frequent to keep the system growing therefore the framework of this approach needs to be very flexible. Furthermore the component deterioration and its operation health will be unique and based on the operation conditions, past repairs and its maintenance. This accurate approach is not available in aero engine component repair feedback.

In this approach the repair knowledge is represented as a design feedback where each node/decision point is represented as frames (notation for knowledge representation systems (framework for representing knowledge Marvin Minsky 1975)) with interconnection giving feedback culmination.

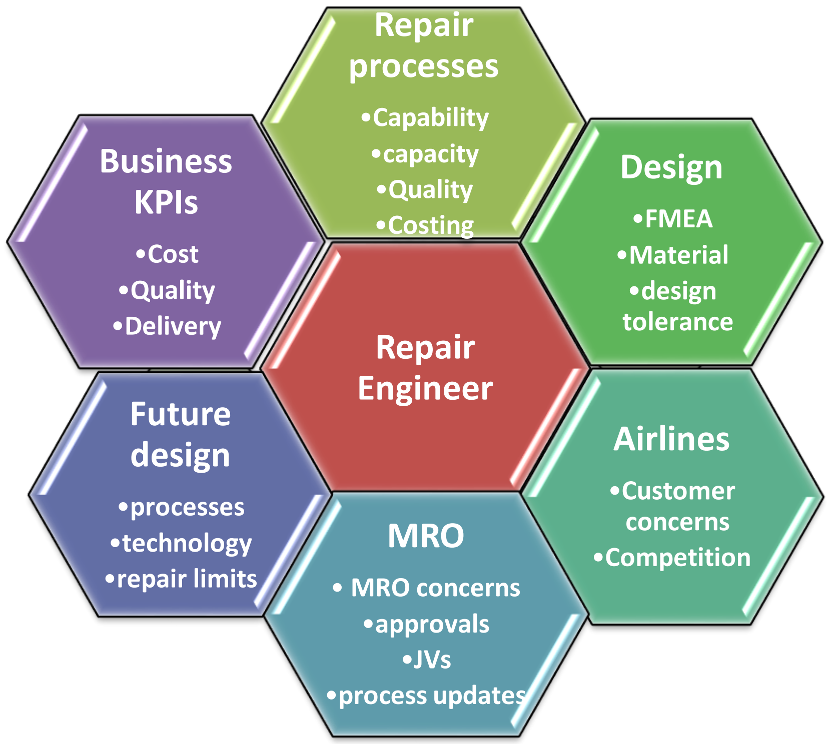


Figure 71 repair engineer knowledge base inputs

The design team may be the responsible for the engine design but repair are mostly facing the design short coming in the service life of the engine, therefore the feedback from many different facets as shown in the figure. Another aspect of the approach is the flexibility to integrate new functionality and features like case based reasoning, update simulation model data interpretation and operational data or condition base monitoring data. The OEMs and MROs need such a system which resolves these challenges (industry survey 2014)

Engine casing was selected as a component to conduct the case study because it offers many dimensions which are required to be tested by the OEMs. Like casing is one of the only commodity which has two extreme ends of the components cost, i.e. the cheap and very expensive, One needing repair throughout the life of the engine the other one only repair if repair offers significant advantage against the new one.

The knowledge base system is developed with close interaction with the service for engineering and the repair teams of the OEM. After the initial design the system will get evaluated by the OEM team to be assessed. Many focus group meetings have taken place in the development of the framework and tool.

6.4 Capturing the Requirements

The main requirement of the repair knowledge capture is what information is required in the design which can be benefiting to the designers at an early stage. The questionnaire and interview were collected from design team supervised by Andy Harrison (service for the engineering of RR) to establish what information is required. The main themes from the data collected are:

- Comprehensive feedback on the reparability of features and functions of the components.
- The limitations of the repair processes based on damage modes of the aero engine components.
- Recommendations of the updates for the aero engine components.

Three level questionnaires were developed to collect the concerns of the repair teams design team and repair technology team. The progressions of questionnaires were managed with the help of manager from repair, design team, lead commodity from services for engineering and manager from global repair systems. The set of expert interviews were collected and codified. At second level semi structured interviews with repair teams for repair technology selection, managed by manager in repair and repair knowledge sharing of services for engineering teams managed by lead commodity in services for engineering. At third level the expert feedback for the validation of the frameworks were tested.

6.5 Identified customers/designers

The casing and NGV design teams are selected for the inputs.

Repair knowledge sharing (RKS repair knowledge sharing); the fact established are described in the diagram 69 for the knowledge sharing framework for the design feedback. The typical repair process is used in aero engine component repairs, the design and manufacturing influence the repair processes in a very traditional manner and there is very less or rarely any feedback occurs between repair and design. Repair focus design updates when there is a challenge in repairing of any component the modification are made in repair process or the design or in the design parameters to carry out repairs. Repair based mitigation is where any updates or any recommendation are made within the design, repair processes and/or in operational conditions comes under repair base mitigations but sometime also come under modifications. Ideal repair process these are the process by which the repair will focus their efficiency and to achieve these repairs will generate some feedback for design. The design feedback is the main components of this knowledge sharing which will provide more effective and efficient engine in the future and will ensure the higher profit for the OEMs

The repair engineer's knowledge can be used as for the feedback intervals to design. This approach focuses the effectiveness and quality feedback to the designer without overloading. These intervals were based on the repair strategy, which includes the repair understanding of

- What features and functions are reparable
- Components deterioration/degradation
    - Repair feedback on "repair mitigation"
- Typical repair processes and its challenges based on components and its damage modes

This kind of concise information would provide the design team a focus from the maintenance aspect.

6.5.1 Repair knowledge sharing elements

The repair knowledge sharing included the aspect of how the ideal repair processes can be implemented on the components and its damage mode, because damage model is one of the single most important factors for component repair.

1) Ideal (preferred) repair processes (based on QCD quality, cost and delivery)
2) A list of the component design updates to implement the ideal (preferred) repair process
3) Repair knowledge user interface
4) Damage modes based on repair intervals

The basic understanding of the designers and repair engineers are similar to the principle. The taxonomy of the engine, commodity and components are well understood across the organisation. Hence the hierarchy of the components and damage mode and the manufacturing/repair processes are common allowing the general and specific formulation and management of the knowledge-base.

The knowledge strategy is adaptable to accommodate situation specific factors influence at any instant of any overhaul, from 1^{st} to 6^{th} i.e. through-life.

The repair initiator gives output specific to the bespoke circumstance, like in which overhaul damage occurred. This provides the system flexibility.

Knowledge sharing reports (repair feedback) these modules extract the feedback to the designers, when the designer would like to access the repair knowledge they will initial the repair feedback.

Repair knowledge strategy:

The reasoning strategies for the repair engineers are mainly contributed by the manufacturers' instructions and the experience of repairing of the specific systems or components. The periodical repairs of aero engine also contribute to the knowledge of the repair engineer to the developing deterioration of components through its operational life. The experience repair engineer develops the knowledge over time where s/he is subjected to the performance parameters for the repairs, all this accumulation of knowledge contributes to his decision making rationales. Thus the knowledge of repair engineers whether it is tacit or explicit, embodied or encoded the main focus is to store it and utilise, as illustrated in the fig 72 by Collins (1993) and Lam, A. (2000).

<table>
<tr><th></th><th colspan="3">Ontological Dimension</th></tr>
<tr><td rowspan="3">Epistemological Dimension</td><td>Level</td><td>Individual</td><td>Collective</td></tr>
<tr><td>Explicit</td><td>Embrained Knowledge</td><td>Encoded Knowledge</td></tr>
<tr><td>Tacit</td><td>Embodied Knowledge</td><td>Embedded Knowledge</td></tr>
</table>

Figure 72 Epistemological Dimension: knowledge types

The idea is to use business KPIs as the reference to examine experienced repair engineers' decisions. It will become easier to evaluate the KPIs base decision and what aspect has significance on those KPIs as all MROs and OEMs are business orientated.

The repair experts uses the cost, quality and delivery requirements given to them from the business to meet as KPI input, and the process performance against the components and its damage mode base on the processes effectiveness and efficiency. Hence the process experts independently assess the process's base on the component, damage mode against the business KPIs to select the best processes to achieve the business targets.

As it is the legal requirement for aero engine must undergo inspection over predefined cycle or operational time (JAR Part-145 (EASA)), when there were granted airworthiness certifications. At this point the repair engineers carry out most of the component level repair, thus collecting the repair knowledge at this point would be best for repair knowledge. It focuses on the expert knowledge of repair engineer when it is most valuable and fresh, i.e. at the point of engine overhauling. Since overhaul is well anticipated by all stake holders it is also well planned. Declared overhauling point for large aero engines are every 3000 flights, each flight consisting of take-off, cruise (6-18 hour) and landing. Every large aero engine gets nearly 6 overhauls in its life.

The strategy has to be adaptable to some degrees of change, the knowledge capturing at the point of the overhaul provide context sensitive flexibility to provide meaningful knowledge to the designers, at what overhaul which damage mode is more challenging and what basic design changes can be implemented to overcome the specific KPIs for the repair. This also allows the repair to the mention a design peculiarity which may be causing the repairs limitations.

The knowledge representation is cumbersome and lengthy task which require many iterations from repair and design, the frame representation suited the most because of varying levels of contradicting requirements of flexibility to the system, also the frame representation does not increase the complexity as the structure increases with flexibility (T.G. Jellison at el 1988).

The directed graphs can be used to represent overhaul with the damage mode at each level each damage mode grows into a different damage mode or the damage increased in the magnitude. The example of this representation is given in the following table, after each overhaul the damage mode is recorded and how it progresses throughout its operational life recorded at different overhaul points:

Table 22: Overhaul based damage mode

<table>
<tr><td>Component</td><td>Overhaul</td><td colspan="3">Damage mode/ deterioration</td></tr>
<tr><td rowspan="5">Casing</td><td>First Overhaul</td><td>Oil staining,</td><td>Attritions lining damage</td><td>Paint damage</td></tr>
<tr><td>Second Overhaul</td><td>Heavy Oil staining</td><td>Heavy Attritions lining damage</td><td>Fatigue lining</td></tr>
<tr><td>Third Overhaul</td><td colspan="2">Light Corrosion</td><td>Fatigue cracks</td></tr>
<tr><td>Fourth Overhaul</td><td colspan="2">Heavy Corrosion/ light structural</td><td>Creep</td></tr>
<tr><td>Fifth Overhaul</td><td colspan="2">Heavy structural</td><td></td></tr>
</table>

6.6 The knowledge sharing structure for the repair feedback

It is paramount to keep the understanding consistence among different stakeholder, especially in knowledge sharing from one team to another like repair to design.

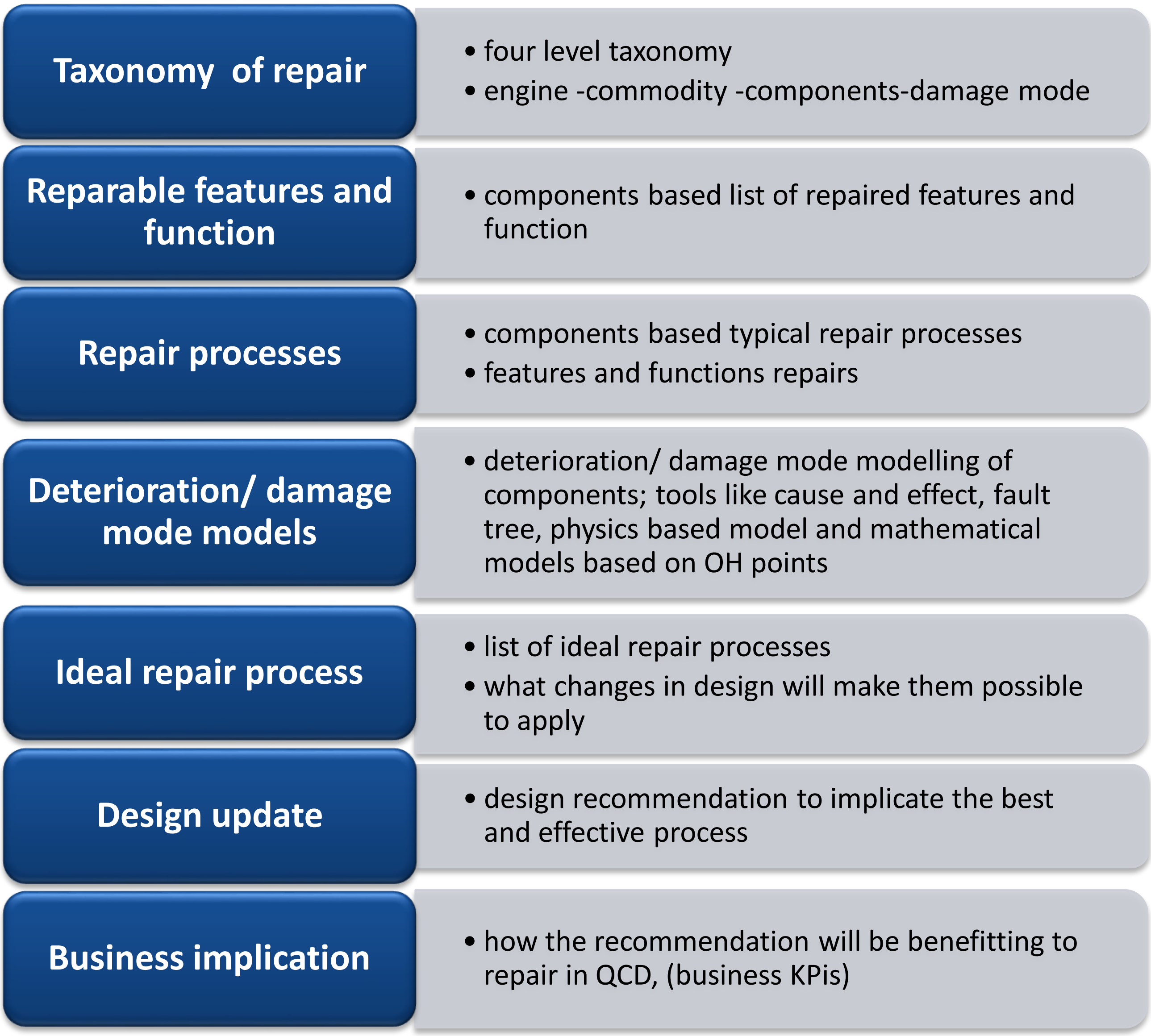


Figure 73 Knowledge structure for repair feedback

The given framework supports all the requirements of the industry and can be referred as what and why knowledge sharing framework. The following sections define the entire framework element in more details.

6.6.1 Taxonomy/ Ontology of repair selection

The repair selection ontology is divided into four levels engine, commodity, components and damage mode to keep the information accurate and structured which can be related to components and the damage mode it is experiencing.

The detailed repair processes taxonomy was developed from the manufacturing taxonomy mentioned above with some modifications. The brief illustration is given in the following figure:

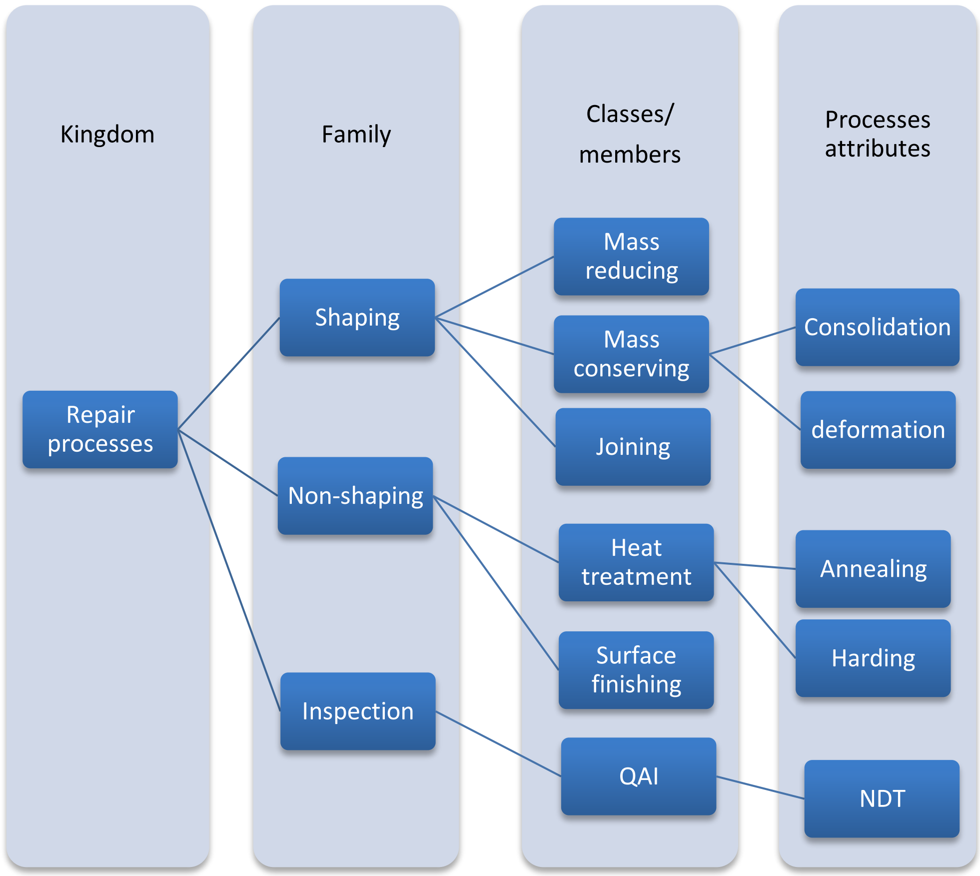


Figure 74 Repair processes taxonomy

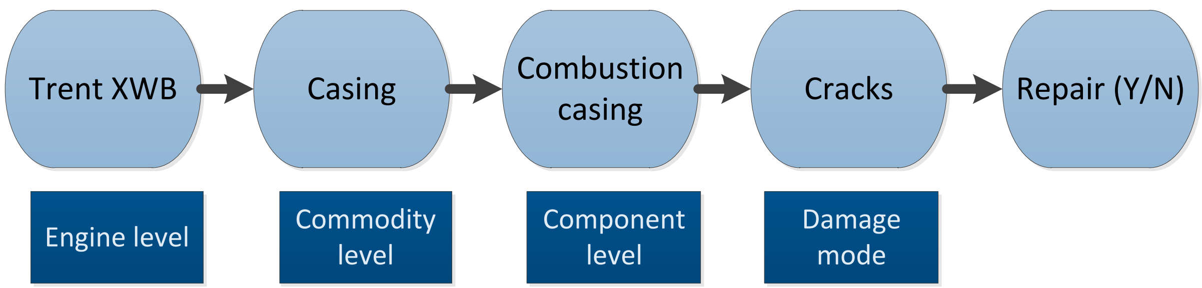


Figure 75 Knowledge sharing taxonomy

- Four level taxonomy

The taxonomy is a basic art of grouping or categorization. It has been confirmed by many researchers to be one of the single most important factors in the knowledge sharing structure. Effective knowledge sharing and retrieval can only be possible by having taxonomy (Lambe, 2007; Malafsky, 2008). Taxonomy is the most critical factor for knowledge sharing. (Pincher (2010))

In knowledge sharing between different team, the taxonomy of the components is predefined for maximising the knowledge sharing that will also embed the explicit knowledge.

Component designers in Rolls Royce are part of a commodity teams, commodity approach is based on different specialist groups within the turbine engine design.

The knowledge sharing between repair and design need a common taxonomy for all the knowledge feedback, hence taxonomy for components is formed by repair by which they will provide the feedback.

Taxonomy for the selected components of the feedback is top to down structure as:

Engine → commodity → components → damage mode/ deterioration

The explicit knowledge embedded in this structure so the tacit part of the knowledge can be reported.

Output: taxonomy

Engine → commodity → components → damage mode/ deterioration

Case study: Trent XWB → Casing → HP casing → Corrosion

6.6.2 Reparable features and function

Once the taxonomy is understood, the repair capacity and capability with respect to components' features and function that can be repaired are reported. In data collection for the knowledge sharing from the Rolls Royce teams, it was observed there are many inconsistencies exist with repair teams which is part of a complex business system. Location, capacities and capabilities based on, from source control repair to control design and processes confidentially. Skilled /cheap labour and material cost could base the location for business, economic reason etc. Therefore, without giving further information, concentrate the knowledge sharing aspect to just list the repair capabilities and capacities for the repair of components.

Components based comprehensive list of features and functions which are repaired and the capacity of the repair. This will give the common understanding to design and repair teams.

Output: components based, list of reparable feature and functions

For example, if the component is HP casing, then the following list of reparable features and functions is prepared.

1. Light & Heavy attrition lining damage
2. Light & Heavy corrosion, and
3. Light & Heavy structural damage

6.6.3 Repair processes

When the feature and functions which are repaired or offered to repair are listed, then current processes associated for those repairs are compiled so that the general understanding of repair and processes capacities are well understood throughout the repair and design teams.

Once the repair processes are linked to the feature and function of components, the deterioration and damage mode can be modelled against the features and functions of the components. The damage mode modelling can feed the latest knowledge acquired; from tools like cause and effect, fault tree, mathematical model and other techniques with processes capacities can be enhanced to repair processes capabilities. This will provide the understanding to give mitigation feedback from the repair team to the design team.

The other feedback at this stage can also report the challenges faced by the repair team based on the design of the components.

Once the components and its damage has been understood the normal or a typical repair process can be shared the aim is to share explicit knowledge through the common structured taxonomy.

The list of activities of repair, based on the Components and its damage would make a design team appreciate all the difference of manufacturing processes to repair processes. As it is a common perception in design that all the manufacturing processes are used in repair which may not be true in all cases. These differences would be the basis of tacit knowledge sharing in the organisation.

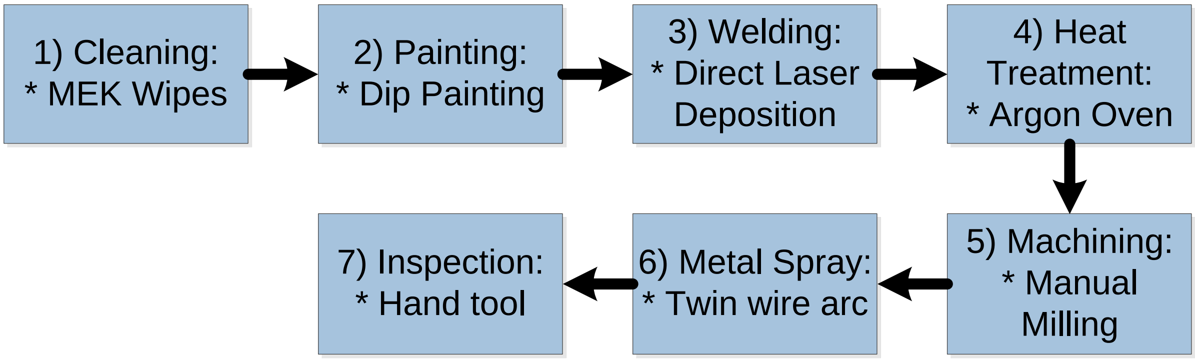


Figure 76 Typical Repair Process

Output: Repair activities; 1) Cleaning: MEK Wipes, 2) Painting: Dip Painting, 3) Welding: Direct Laser Deposition, 4) Heat Treatment (H/T): Argon Oven, 5) Machining: Manual Milling, 6) Metal Spray: Twin wire arc, 7) Inspection: Hand tool

6.6.4 Deterioration/damage mode Models

This section in the knowledge sharing would accumulate the information which will also include the tacit knowledge of the repair engineer. This knowledge will give the design team the insight of the real service life behaviour of the components.

The repair team overhauls large aero engines around five times in its life. This presents the opportunity to record the deterioration on every overhaul from repair prospective.

Diagnosis and prognosis can be effectively recorded by directed graphs explained mathematically by Fan Young et.al. 2012. Michael Halasz et al. 1992, used directed graph to develop knowledge-based approach maintenance for mechanics of jet engine. Therefore the component deterioration can be recorded very comprehensive by repair teams over the life of the aero engine. Many engines are in a different age of overhaul, the same engine can also be used for prediction of other engine component deterioration for internal planning and knowledge sharing for the design team.

Output: damage progression is shown by use of directed graph in the table, first overhaul seen the oil staining, attrition damage and paint damage these damages were progressing as heavy oil staining, heavy attrition damage and heavy paint damage respectively. More details are presented in the table below

Table 23 Repair and overhaul based deterioration evolution

Component	Overhaul	Damage mode/ deterioration		
Casing	First Overhaul	Oil staining,	Attrition lining damage	Paint damage
	Second Overhaul	Heavy Oil staining	Heavy Attritions lining damage	Fatigue lining
	Third Overhaul	Light Corrosion		Fatigue cracks
	Fourth Overhaul	Heavy Corrosion/ light structural		Creep
	Fifth Overhaul	Heavy structural		

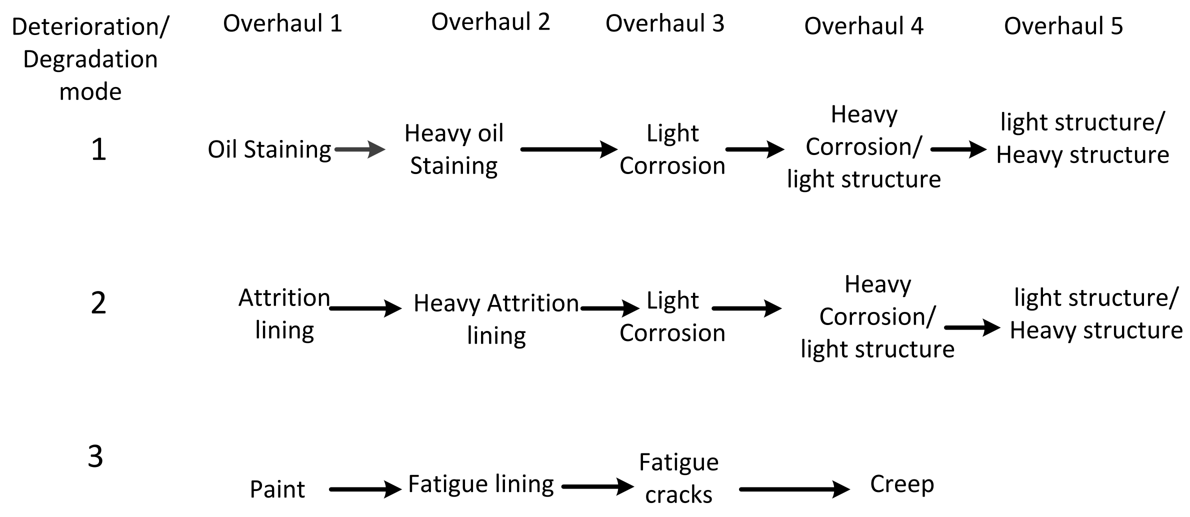


Figure 77 Directed graph based degradation evolution

6.6.5 List of Ideal (preferred) repair processes

After having the latest repair processes' capabilities and capacities with the features and functions associated with damage modes the repair team can compile design updates which can give them the opportunity the employ the effective repair processes to repair components. This will include why those repair processes are not yet implemented and how the repair team recommended design update will translate into business KPIs (as mention; the assessment criteria based on QCD) or what benefits are captured in term of business efficiency, enables and disables of repair processes with reason or related notes based on the overhaul point of repair for the components. Therefore the final feedback from the repair team to design will include the design update vs. what the business benefits are captured as reflected in the table below

- List of ideal repair processes
- What changes in design will make them possible to apply

A lot of research has been done in the process selection for manufacturing (from developing new processes to mature processes), but repair process selection has been largely neglected, due to lack of knowledge sharing (UK MRO market research report 2014).

There are many differences between aero engine component manufacturing process and component repair processes. The critical aspect of repair and manufacturing may sound similar but they are very different. Some common considerations for manufacturing are shape, material, tooling cost, time, and production volumes. All these considerations are from a design point of view. In repair these are from the considerations of service, operations and maintainability. Basic technical understanding of tolerance in manufacturing and repair are very different and largely misunderstood (Simon 2015 RR) Hence processes selections in repair are very different from manufacturing.

One of the other factors came into light from the repair focus group discussion was, often the cost of repair gets more focus and attention early in the repair process selection and long term benefits are ignored. Case study of NGV repair from brazing is an example, where re-repairing become a challenge. Therefore, effective repair must consider knowledge sharing with all teams more consistently.

Output: the list of the ideal repair processes based on components and its damage which will benefit the repair team to achieve their performance targets.

Trent XWB → Casing → HP casing → Corrosion

Ideal repair process; Repair activities; 1) Cleaning: MEK Wipes, 2) Painting: Hand Painting, 3) Welding: Electron beam welding, 4) Heat Treatment (H/T): Not required, 5) Machining: Automatic NC Milling, 6) Metal Spray: Plasma, 7) Inspection: GOM

6.6.6 Repair mitigation and designs' update

Design recommendation to implication the best and effective process

The designs for assembly and manufacturing have been around from more than two decades (Boothroyd.G, 1980), (G. Boothroyd, Marcell Dekker, 1992). There are some aspect of repair have been addressed in DFA (design for assembly) but from the repair process identification has been overlooked. Repair teams from aero engine MRO can play a crucial role in the design of aero engine.

Most of design uncertainty models for physical components are based on service knowledge (Aparna. Gupta, 2008). The MRO is well equipped with the technical knowledge; hence the repair knowledge sharing must play an important role for design updates and design for repair, from service and repair attributes. The lack of knowledge bases is a prime challenge for the jet engine improvement (Philip Scranton. 2006).

Thus the repair involvement in design is ever so much for not only design improvements, but also for the business competitiveness and environmental considerations. Furthermore, business KPIs driven repair recommendations can greatly improve the repair capacity and compatibility of aero engine repairing,

Output:

Table 24: Component based design recommendation

S. No	Component	Design updates
HPC1	HP compressor casing	Thicker surfaces
		Metal spray aspect ratio 1:10
	HP TB	Thicker coating

6.6.7 Business implication

- How the recommendation will be benefitting to repair in QCD, (business KPIs)

Business implication is the dimension of the business acumen from repair world which can offer a meaningful justification of the recommended design updates.

Knowledge sharing part in this section will report how the design updates are helping the business in future designs output:

Table 25: Component base design recommendation for KPI benefits

S. No	Component	Design updates	Business KPIs (QCD)	Details
HPC1	HP compressor casing	Thicker surfaces	Offers no repair required in 1 and 2 overhaul visit Longer component life	OH 1 100% savings OH 2 100% savings OH 3 process flexibility, saving 50% savings
		Metal spray aspect ratio 1:10	Any metal spray process could be used offering improvement in all QCD	Process flexibility, saving 40% savings
	HP TB	Thicker coating	Can last extra 3000 flights	OH 1 100% savings

6.7 Case study

There is embedded case study in the framework development used as example at each element output.

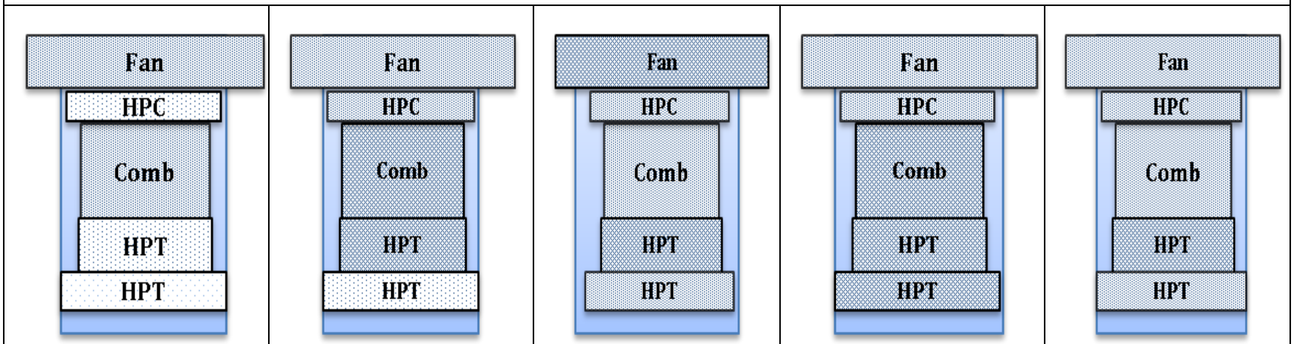
The repair of HP compressor case is described and knowledge is captured by repair engineer in the engine design. The repair engineers' knowledge was captured at every point of an overhaul.

The repair challenges at each overhaul point are recorded with disabler and enablers also giving brief descriptions of each reason. In aero engine components' repair, it is done on the engine overhaul. Typical large aero engine undergoes 6 overhauls in the lifetime, each overhaul is roughly take place around 3000 (3k) flights, each flight includes take-off 6hr-18hrs cruise and landing. At each engine overhaul not all the components are repaired. The ideal overhaul for repair is to examine the component clean it and reassemble it. Based on different damage maturity following table 26 shows what commodities and components do get repaired. This also shows the complexity of repair knowledge gathering.

The components within the aero engine have different damage maturity based on engine maturity and can be illustrated as:

Table 26 Components' Damage Maturity

1st Overhaul	2nd Overhaul	3rd Overhaul	4th Overhaul	5th Overhaul
Components damage maturity based on engine maturity				



Damage	**None**	**Light**	**Medium**	**Heavy**

Table 27 Rolls Royce large engine history of overhaul based on modules

Engine module (Commodity)	1st Overhaul	2nd Overhaul	3rd Overhaul	4th Overhaul	5th Overhaul
Fan	✓		✓		✓
Gear box	✓		✓		✓
IPC	✓		✓		✓
High Pressure (HPC, Combustor, HPT)	✓	✓	✓	✓	✓
IPT	✓	✓	✓	✓	✓
LPT			✓		

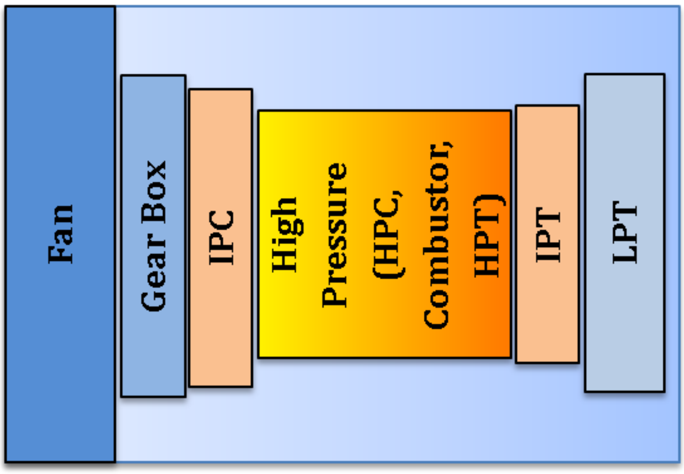


Figure 78 RR engine modules based on repair

The case study for HP casing is given to demonstrate that components repair knowledge can be collected to provide the engine level understanding and the comprehensive feedback to designers. But as far as the component repair feedback concerns the following case study provides the repair knowledge framework as a proof of concept

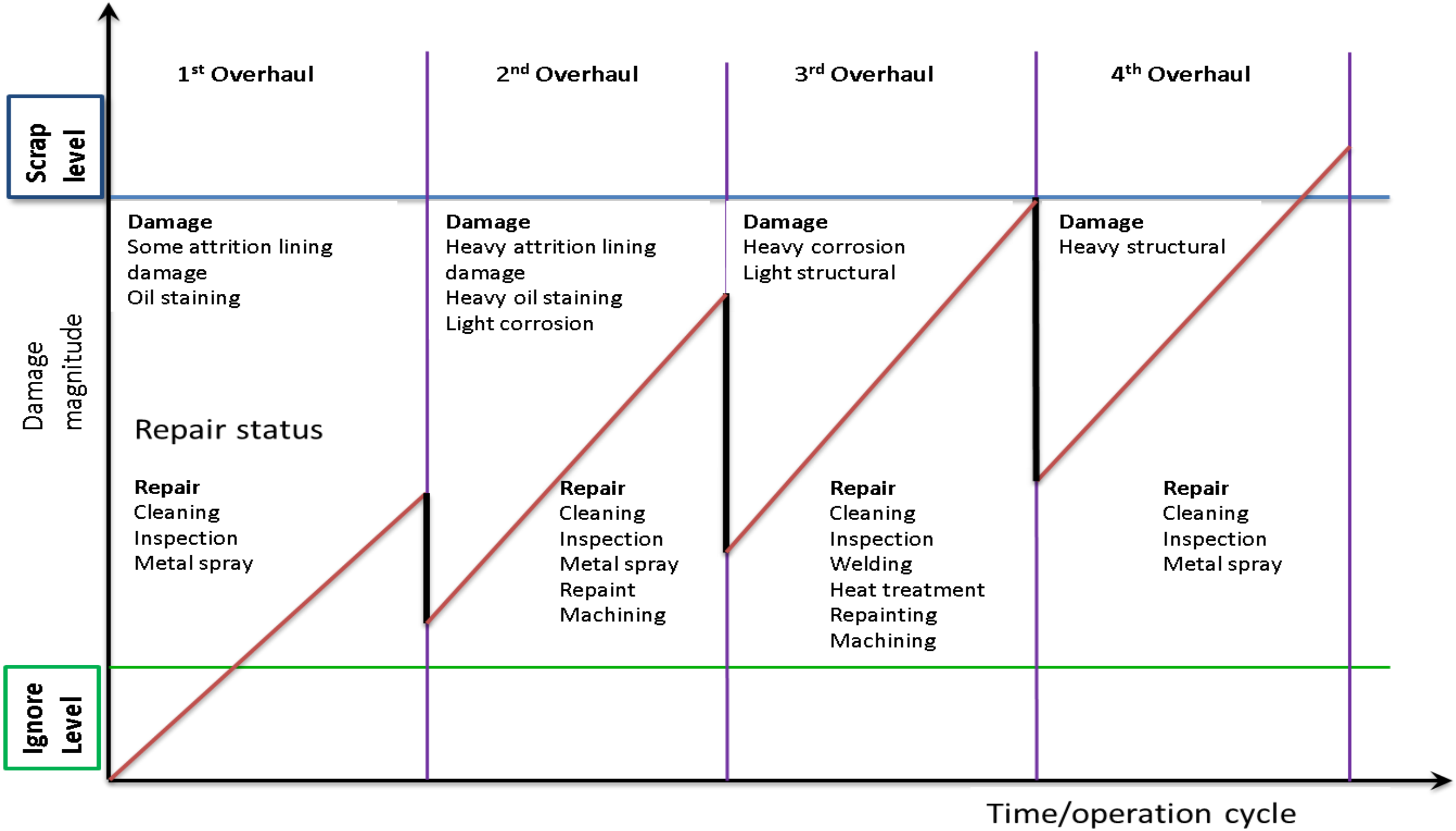


Figure 79 HP casing overhaul life cycle

Chapter 7

7 ORSS Validation & results

7.1 Validation approach

The intention of this chapter is to express the validation of the optimised repair selection strategy (ORSS) and W2 knowledge sharing framework, from the industrial case study and focus group. Furthermore, this approach of the validation was also the industrial requirement of this research. Every validation case was cautiously selected to focus the relevance to existing engineering challenges. The validation has two distinctive parts, one deal with the ORSS and the second one validated the W2 knowledge sharing framework.

7.2 ORSS validation

ORSS validation has two levels; first level compares the historical cases which are updated through the evolutionary process, the updates are made as per required or requested through past cases. The second level was taking the subjective cases from different departments of repair engineering and comparing the results of framework with expert focus group decisions. This method of validation solves the engineering challenges at practical level where they have learnt from past (i.e. employing repair expert knowledge in making decisions) and update the decision and if new repair method is employed the expert will be called upon to make the effective and efficient decision. Therefore, the ORSS framework is competitive at both levels.

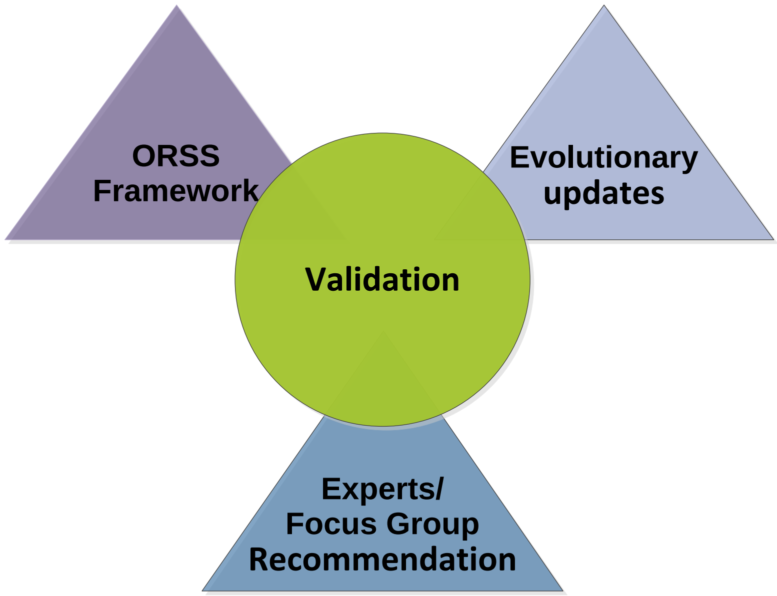


Figure 80: ORSS Validation method

7.2.1 Framework validation from evolutionary updates

The repair selection is an evolutionary process; all repair processes are subjected to the technological change with financial impacts. Whenever there is technological or financial impact on any repair process considerable updates are required by industry and OEMs alike.

The ideal validation for ORSS is to take such cases where these updates are applied by giving financial and technological information, if the ORSS framework makes the same decision as they were taken historically after careful consideration, which will prove that the framework is valid.

Two such cases were selected where the repair departments were asked to reduce the cost of repair.

7.2.1.1 Case 1

Component A had been getting repaired, but it was costing very high to Rolls Royce. The finance department asked to reduce the cost of repairing for this component. The repair and process expert teams run a lengthy exercise, especially for this request. The expert team concluded and updated the repair processes for the component they made considerable updates in the repair process. The same parameters were inputted in the ORSS framework to examine the same or similar output as the results of the expert teams. ORSS selected precisely the same processes as the concluded repair process for the components by the expert teams. The output of the tool is given for illustration in the fig below

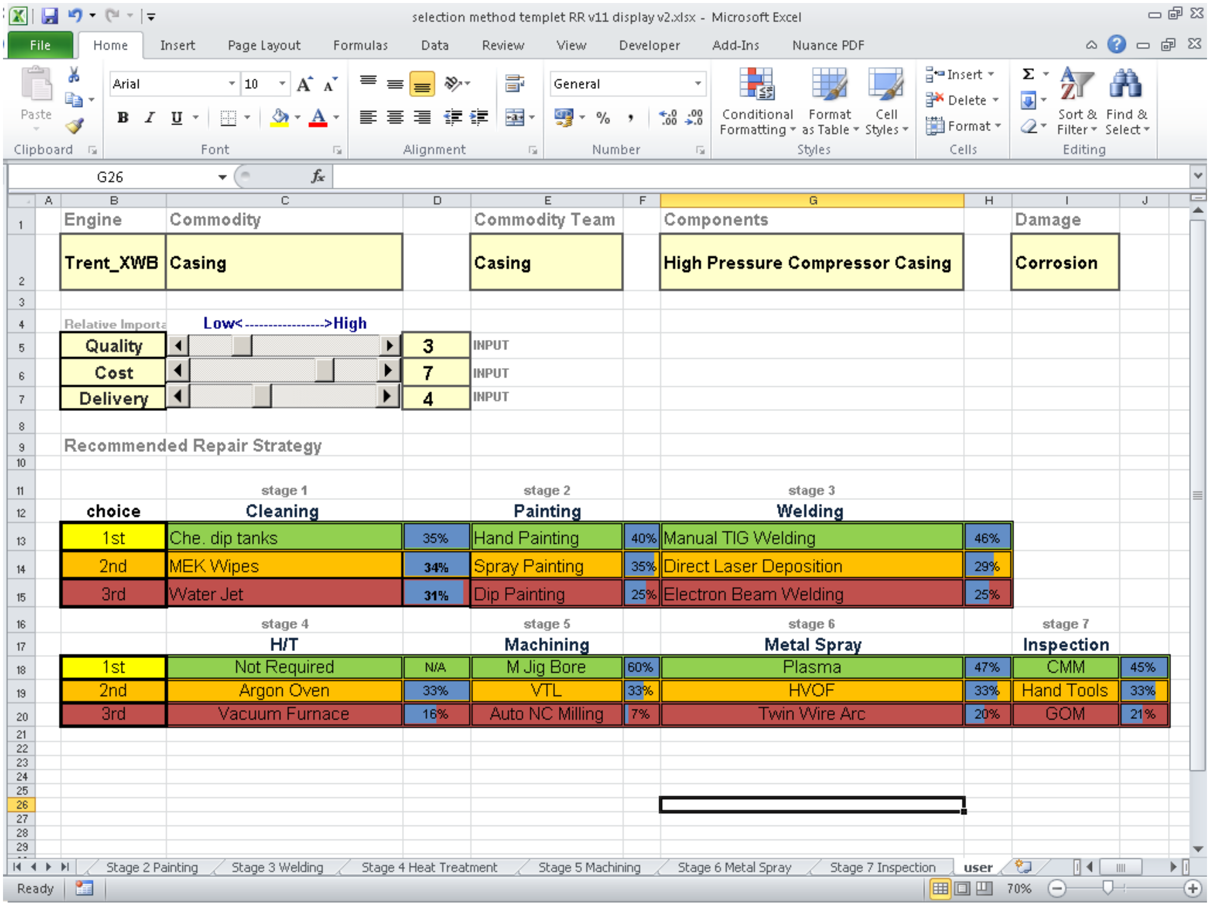


Figure 81 ORSS output for validation of case 1

The repair experts confirmed the validity of the tool and the selected case.

7.2.1.2 Case 2

The same exercise was conducted on component B the result were as promising as for the component A. The output sheet of the tool is given below

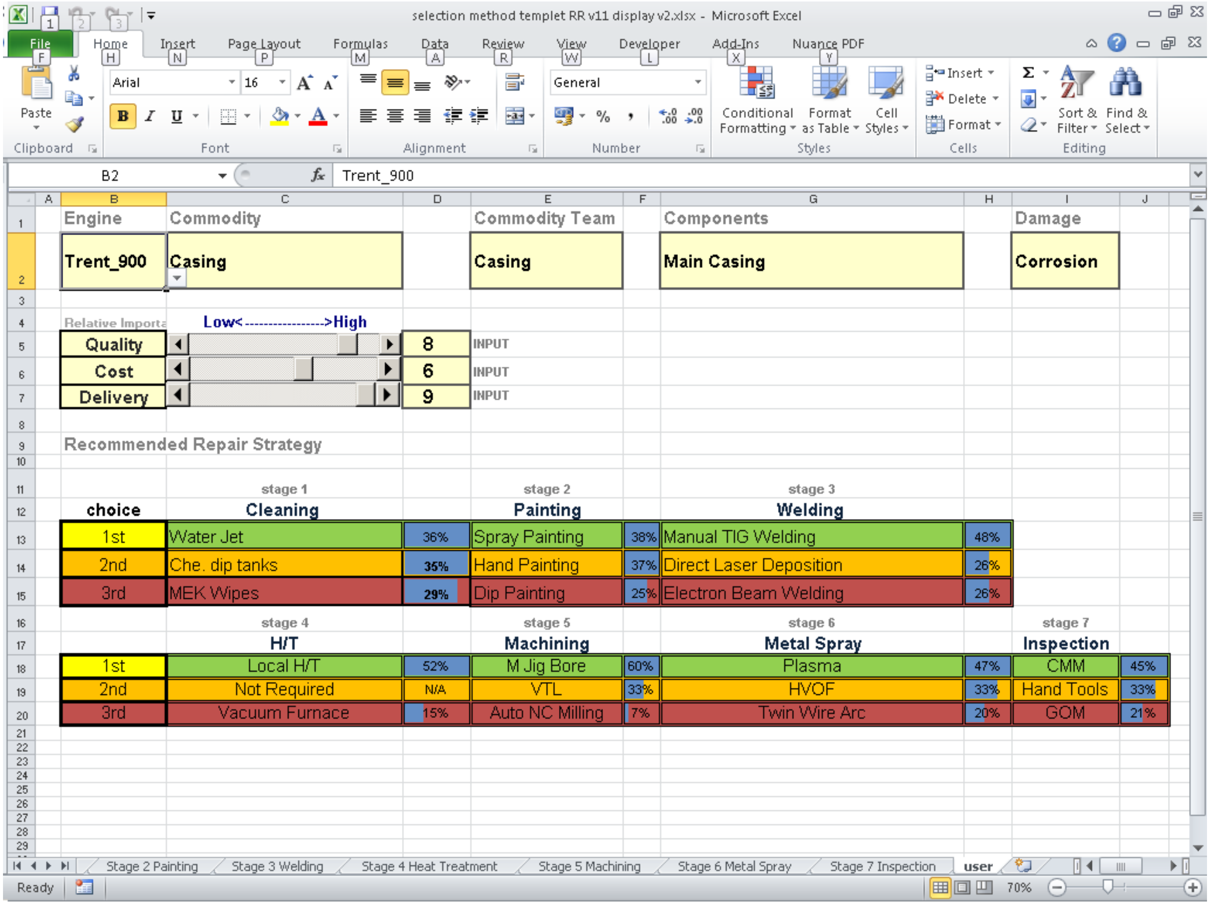


Figure 82: ORSS output for validation of case 2

The repair experts also confirmed in writing the validity of the tool and the selected case.

Both of the above cases used different turbine engine different component.

7.2.2 Expert/focus group validation

The repair experts at Rolls Royce were given a task to suggest optimised (effective and efficient) repair process for a selected component with specific damage mode. The component and damage mode were carefully selected.

The repair experts' results

Table 28 Repair expert selection

Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7
Cleaning	Painting	Welding	Heat Treatment	Machining	Metal spray	Inspection
MEK wipes	Hand painting	TIG	N/A	Jig Bore	Plasma	CMM

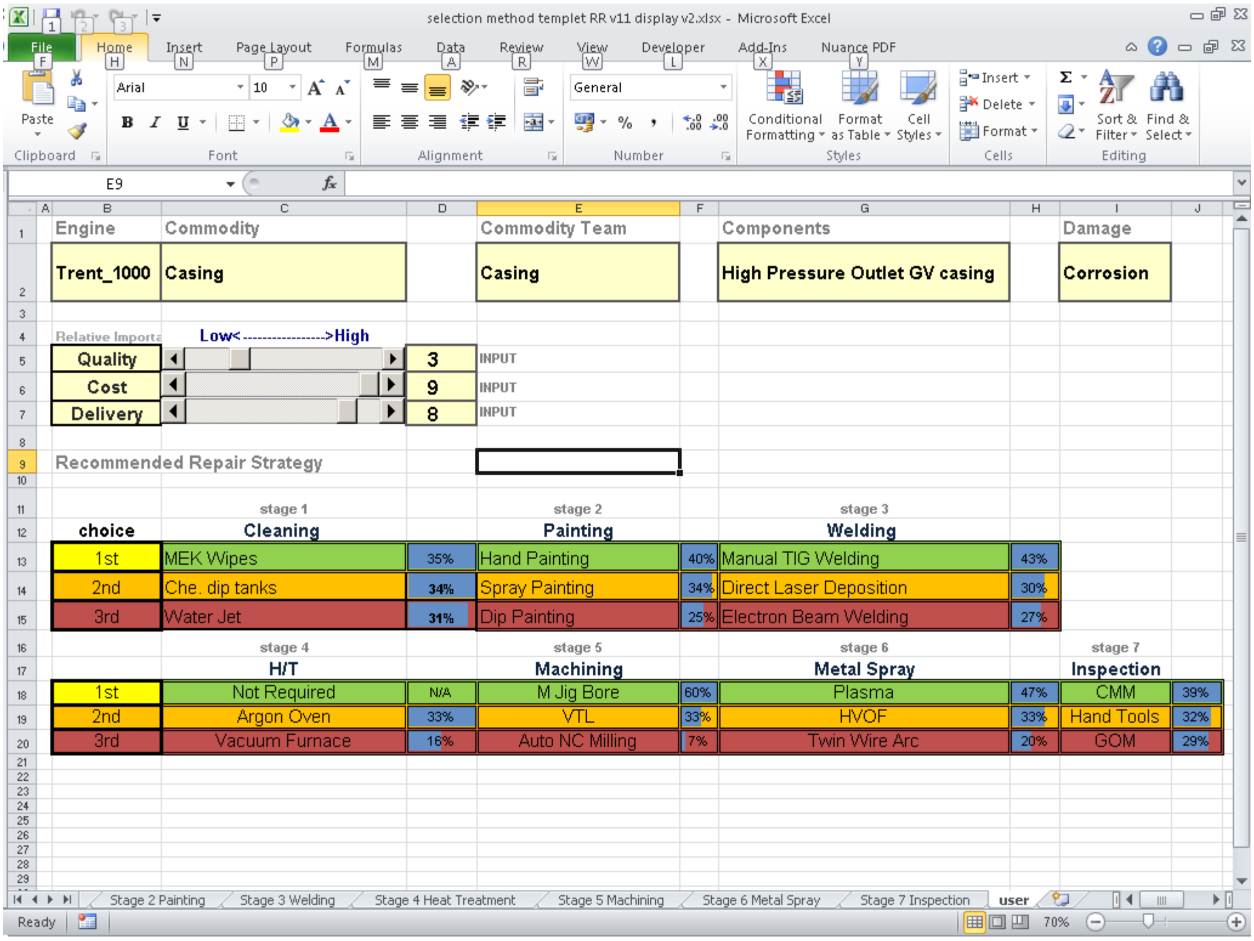


Figure 83 ORSS output for validation of experts

The results were overwhelmingly similar. It has to be said that there is a bias existed in some terms of scoring and assessing the repair methods, but overall the selection was similar if not the same.

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Chapter 8

8 Repair knowledge sharing framework validation

Second part of the validation is the repair knowledge sharing. It was denoted as W2 repair knowledge sharing framework (W2 framework in short). The two elements of feedback were what and why of repair knowledge.

After taking intensive utilisation of the W2 framework to prove the validity, there were staggering discoveries from the repair engineers. It was also startling that before W2 framework, feedback loop dose doesn't extend to repair in a comprehensive manner, hence these discoveries were made which are listed below and details were discussed previously.

8.1 Repair Knowledge sharing

This framework supports the aero engine designers from the repair knowledge during the design process. This study included the requirements of repair knowledge sharing.

The requirement developed during the formative phase of the research, which is based on the analysis of different information collection activities;

Exploratory semi structure interviews from repair and design teams and investigation of different selected components with repair experts.

The requirement for the validation had two reasons, 1) to verify the analysis, 2) to provide effective repair knowledge sharing, report anomalies and challenges.

This study also fulfils the research objectives for the repair knowledge sharing, effective repair knowledge sharing to design.

This section discusses the design consideration and the results of appraisal sessions based on different components and repair process/technologies.

(Due to strict confidence and NDA the information needed to be desensitised and suppressed).

8.1.1 Validate Design for repair knowledge sharing

There are many plausible factors to consider, there were three important factors considered for repair knowledge sharing validation. Those are:

- Achieving the aims and objectives by validation
- Scope of validation: keeping the repair knowledge as a primary feedback to designers
- Validation design consideration

8.1.2 Aims and objectives

The repair knowledge sharing, validation initiated from research objective five, to verify the postulations developed. Consequently, model connotation would result from validation:

- The repair knowledge requirements recognised (what and why of the repair processes and design updates are required) would be adequate to enable preliminary feasibility assessment of the repair knowledge sharing to be conducted at early design stage.
- The repair knowledge level would be appropriate for preliminary feasibility assessment at early design stage.
- Repair knowledge sharing could be defined as sequential steps to ideal changes in repair processes/technologies and component design.
- Mixture of different knowledge kinds could be used to define the ideal process or update to component design.
- These combinations would be an effective way repair knowledge sharing to design.
- This validation would allow the effective gathering of the repair knowledge.

The effective means that the validation was with the agreement of repair and design teams consent and can be gathered quickly and efficiently. The other aim was to assess the fitness of the validation in effectively defining, obtaining and sharing repair knowledge for the early design stage. This also means that the application of validation would need to be practical.

Hence the objective of validation is to design appropriate situation which would allow the validation to be applied to a suitable range and number of scenarios where suitable repair knowledge could be prepared and feedback to design. This would validate both the postulations and validation. To plan and apply a method of information collected during the validation to check the attainment of the six connotations mentioned above. Therefore the aim and objective inclined both the scope of validation and the design of validation.

8.1.3 Scope of the validation

The scope of validation consists of, the process of validation which is applicable and keeping the repair knowledge as a primary feedback to designers and keeping the validation in the practical context.

For achieving the ideal results as explained earlier, the repair knowledge would need to be found and obtain. The obtained repair knowledge needs to be evaluated for its suitability for the early design stage by the designer. This validation took the form of qualitative case study (Pamela Baxter and Susan Jack 2008).

8.1.4 Validation design considerations

As explained in research design the formative evaluation was used and fits the requirements of Patton approach (Patton 1987) It comprises select and create which is seen as what and why in the w2 framework and the process strategy in accumulating the required knowledge. These strategies need to employ qualitative data in order to provide comprehensive understanding. The other element in this approach is; what is signifies knowing, what information would be necessary and how the design be suitable to compare with validation. It also emphasizes the critical needs of the stakeholders.

The validation aims to consider the whole w2 repair knowledge sharing framework. With the framework, it also takes what and why processes require greater details. The questions arose in what and why were:

- Is the effective mode of emphasising the components which may require extra analysis?
- Is the repair knowledge reliable from repair to design?
- Does it features inherit the repair knowledge prerequisite for early design viability evaluation?
- Is the level of details according to the requirements?
- How the different understandings effect the collected knowledge?
- How effective is the framework is working?
- Assessing the repair knowledge acquired, does it provide repair knowledge to the correct understanding to design which are useful at early design stage?
- How the different types of knowledge do affect the design and its uses?

Baring these challenges in mind, it was practical to validate the framework as a real example to examine how the framework would be perceived in real life situation. Furthermore the framework with real component as an example would provide information about the level of detail and effectiveness in repair knowledge sharing to design at an early stage.

This is also supported by Patton, M. (1990) where it describes, as a purposeful sampling in qualitative validation with the support of information-rich case studies in depth (Patton, M. 1990, pp 169-186).

8.1.5 Validation Design

As discussed earlier, the validation was designed to identify what and why of repair knowledge sharing relating to component through life case, each repair of the component for its degradation at each overhaul with different repair technologies and process.

The components used for validation was the combustion outer casing repair and front Bearing housing over typically 4 -5 overhauls each overhaul had a different damage mode with different level of maturity of damage.

These components use the maximum available repair processes with different level of technology.

Therefore, this could be extended for a similar component for different engines and the relation between the degradation and its repair with repair knowledge accumulated by repair can serve as a further input to design with greater confidence to update the component design, furthermore it will also provide the greater financial benefits in future component design.

These components were intentionally chosen to prove that the framework can be used for a variety of components and address the reported challenges. They offer many different damage modes, multiple repair processes with different level of maturity and different level of repair yields. Beside the technical reasons the financial reasons were equally important, these components also provide the opportunity to examine low cost component where the damage is critical to decide whether to repair or replace and for a high cost component where repair is must but how to assist the design for less wearable design in future with low cost repair.

Two stages of evaluation for the framework were required, the first stage was the appraisal of the knowledge recognition and realisation phase of the framework mentioned as what and why aspect of repair. This was called repair knowledge evaluation, indicating the repair knowledge to be collected. The second stage was the evaluation of the gathered knowledge to determine its aptness for the early design stage usage. This was called design evaluation, where, what and why aspects of the gathered knowledge questioned. The further details are discussed in each section of repair and design knowledge evaluation.

8.1.6 Repair knowledge evaluation

The aim of this stage is to simulate the actual situation as far as possible; hence the framework was used as planned for the practical situation for different damage mode with varying repair processes. The people involved were repair experts for the given components with significant experience, exposure to repairing these components and had a lead role. Therefore the information collected was as real as it can get so that the experts can examine the repair knowledge framework (w2 framework) for proof-of-concept.

The purpose of the repair knowledge evaluation was the recognition and realisation (what and why) of repair knowledge repair wants to feedback considered useful to early design stage. These activities were carefully designed because most of the information was sensitive either commercially or technically. Each time repair knowledge framework was explained to acquire what repair knowledge can benefit repair to achieve their performance targets at each stage of repair overhaul, which included:

- Taxonomy of repair to eliminate the misunderstanding of any similar named components
- Reparable features and function of the components to keep the repair understanding common to design understandings
- Repair processes to minimise the ambiguity of repair processes used for designer knowledge also to bring both teams to a common understanding of processes used
- Deterioration/ damage modes to edify the designer for real repair challenges faced on a daily basis.
- Ideal repair process to inform designers what repair process would be more applicable
- Design update to provide repair focused design updates t
- Business implications for repair to provide the business and financial challenges confronted by repair

The example of the framework explained to repair expert is given below:

1. Taxonomy of repair

- four level taxonomy
- Engine - commodity - components - damage mode

2 Reparable features and function

- components based list of repaird features and fiunction of components

3 Repair processes

- components based typical repair processes
- features and functions repairs

4 Deterioration/ damage mode models

- deterioration/ damage mode modelling of components; tools like cause and effect, fault tree, physics based model and mathematical models based on OH points

5 Ideal repair process

- list of ideal repair processes
- what changes in desing will make them possible to apply

6 Design update

- design recomendation to implication the best and effective process

7 Business implication

- how the recommendation will be benefitting to repair in QCD, (business KPis)

Figure 84: Repair Knowledge Framework

The example of the repair knowledge out is given in graphical form below

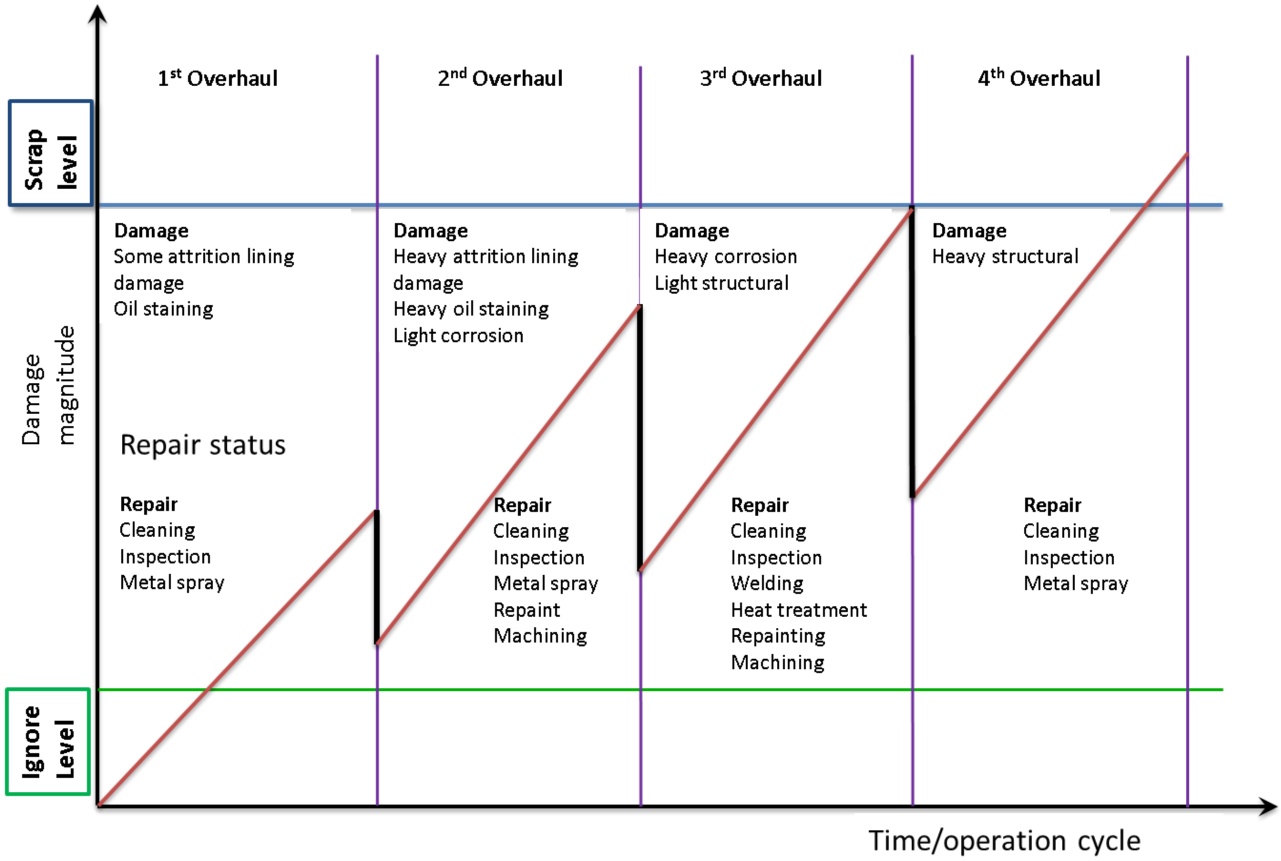


Figure 85 combustion outer casing repair knowledge output

8.1.7 Design Evaluation

The aim of this stage was to evaluate the feedback of repair knowledge evaluation as the output to examine its aptness to be used as repair knowledge sharing input for design at an early stage. In essence, how the repair knowledge can mould for design use. Therefore the people involved in this stage were expert, but also with experience of dealing and conveying the customer consents to design teams and also exposure to the servicing element of the component to appreciate the repair knowledge and its uses. This was very beneficial for the framework validation specially the 'repair knowledge sharing' element of whole research; it also provided the verification of proof-of-concept for the framework. The purpose of the design, evaluation was the recognition and realisation (what and why) of repair knowledge design wants as a feedback considered useful to early design stage. To aid this process the repair knowledge was presented in tabular form. This tabular form was used to represent the repair knowledge simpler and comprehensible as the result of earlier input while developing the framework.

Repair knowledge output was examined very carefully for its suitability, effectiveness and usability for designers and verified by expert to be effective in the design at an early stage. The output tables are arranged in overhaul and repair process basis for the given component. Therefore, it is very easy to examine what are the challenges of repair stages and damage-modes for the given components are, furthermore, it was also appreciating the repair and design weakness at the same time.

Accumulation of all components repair knowledge sharing also provided the engine degradation for different component at different overhaul with picture of damage maturity as presented in the figure below:

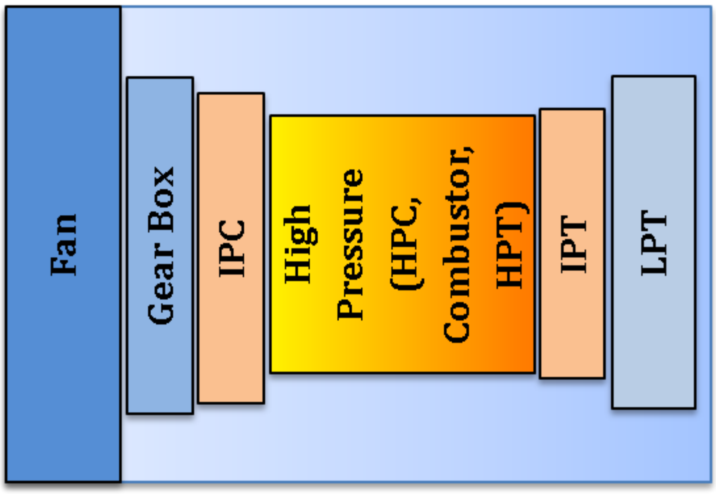


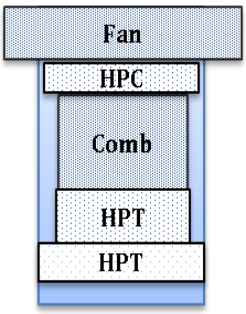
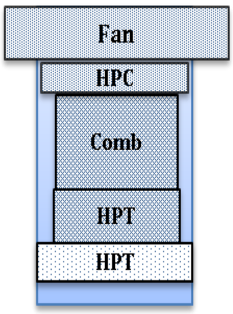
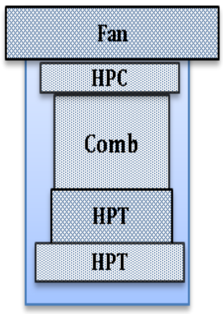
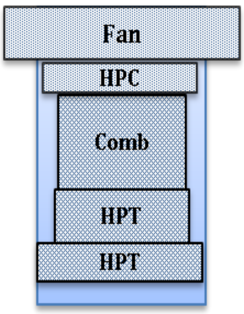
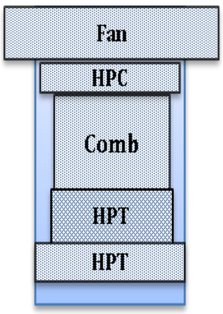
Figure 86 RR engine modules based on repair

Table 29 Rolls Royce large engine history of overhaul based on modules

Engine module (Commodity)	1^{st} Overhaul	2^{nd} Overhaul	3^{rd} Overhaul	4^{th} Overhaul	5^{th} Overhaul
Fan	✓		✓		✓
Gear box	✓		✓		✓
IPC	✓		✓		✓
High Pressure (HPC, Combustor, HPT)	✓	✓	✓	✓	✓
IPT	✓	✓	✓	✓	✓
LPT			✓		

The repair knowledge output also helps the designer how the engines are wearing over the different overhauls. The following example provides the how different modules of the engine are wearing out after the recommend MRO so the appropriate design update can be considered.

Table 30 Rolls Royce large engine history of damage based on modules

1^{st} Overhaul	**2^{nd} Overhaul**	**3^{rd} Overhaul**	**4^{th} Overhaul**	**5^{th} Overhaul**
				
Damage	**None**	**Light**	**Medium**	**Heavy**

Chapter 9

9 Discussion

The key aim of this thesis was to develop optimise repair strategy selection and repair knowledge sharing to support aero engine design. Chapter 4 recognised through interviews, focus groups, and questionnaire that the aviation industry requires decision optimising solution for processes & technology selection for repair teams. Whereas chapter 6 focuses the repair knowledge sharing aspect of the thesis.

It was recognised by expert focus group that there is no tool/technique available to repair engineer assist in process selection. It was clear that repair engineer process selection decision does not have much safety implication, the less optimised decision impacted the cost. The main reason of less optimised decision are mainly due the workload and complexity of the criteria. There is a bias among the repair engineers for technology/ process selection.

The knowledge sharing also have many challenges. There are many differences between repair (MRO) and design teams, apart from cultural, work practices, epistemological there are technical and design understanding differences which most of the time are overlooked. The repair teams' inputs perceived less important as they may not address the design concerns at the early design stage from the design point of view. It has been proved many times that the repair knowledge sharing carries bigger impact not only for design, but also for the business longevity and maximising the shareholder values in recent times. Chapter 4 identified through qualitative analysis that OEMs and MROs needs an optimised process selection solution for repairing that can assist swiftly for complex decision. The research recommends the ORSS, business and operational level (repair) optimisation and knowledge sharing framework.

The Repairing of Mechanical components depends on many factors I.e. cost, effectiveness of repair, the rate of deterioration, safety, design specifications, tolerance, operational conditions, amount of repair needed, processes required to carry out the repair, environmental considerations and many other factors. Eventually the aim of the repair is to recapture the life of the component or fix the function and the feature of components to a safe operational performance. This research has explored that the critical advantage can be achieved through employing better repair strategies. These repair strategies can be applied within the repair selection strategy, knowledge sharing to the designers to gain strategic advantages.

The scope of the research is in large civil aero engine repair strategy selection and knowledge feedback from repair to design.

Starting with the background of why and how aero engine service sector is increasing from the evidences from industrial updates, business cases and forecast reports. According to conservative estimates, the service sector will grow to around 60% of the revenues of OEMs, Airlines are making highly informed decisions and demanding efficiency and effectiveness within the OEMs lead MRO activities. Therefore, this research has very strong industrial appeal and implication for the future.

The maintenance has become the main activity of OEMs to generate extra revenues and profits. The main difference between traditional maintenance and servitisation (the modern approach of maintenance) is aero engine are sold with the maintenances option with OEMs responsibility. It also increases the value in the product for the customers and OEMs. Since the OEMs have taken the maintenance responsibilities the aero engine deterioration has become a very important concern because the maintenance cost also impact the OEMs. The optimisation in maintaining the aero engine has opened many challenges and opportunities for the OEMs. The maintenance of aero engine has considerable high repair costs, with added values of the feedback for the OEMs to develop the aero engine longevity.

The engine operations deteriorate and degrade its performance, the reduced performance requires higher fuel burn and high temperature operations, which deteriorate and degrade engine more and more. The repair strategies are designed for the engine repair which needs to recoup engine performance efficiently. Furthermore the industrial case study in chapter 4 shows many common damage mode and their repair with multiple criteria are studied. While repair selection can be optimised by MCDA, the opportunity to use this knowledge to be incorporated in the design will also provide great benefits to OEMs in longer terms. Therefore the designer can think more carefully with repair inbuilt option in the design of the aero engine. Multiple criteria selection is gaining a lot of attentions from the operational management and it has many techniques. Among these techniques AHP is researched by many academic due to its versatility. The ability of solving the multiple criteria challenges with very less data is desirable for the researchers. It also offers the experts uniquely quantifying according to business and/or technical needs without much effort.

The industrial practices were studied and completed by case study analysis, semi-structure questionnaires, and interview with the experts. The repair expert with good understanding of cost and technology were selected to assist in designing a repair selection framework and initial study was done for the repair process selection. All the processes available for repair are considered and ranked on the basis of business KPIs. Then the repair engineers will focus their business KPI targets based on the component. The selected business KPI were QCD; Quality, Cost and Delivery.

As discussed in the literature review section the different multi criteria selection method can be used in repair process selection. AHP was selected as a pilot study for proof the concept.

All the repair activities were assessed against QCD and ranked by repair processes expert and repair engineer will give the required QCD to meet the business KPI targets. This was repeated at all repair stages/activities and the findings are given as block diagrams to illustrate the framework foundations. The detail explanation are given in chapter 5.

Repair Processes Selection for Aero Engine Component: Once all the repair processes are defined and evaluated, the repair scheme or Repair selection strategy can be determined by combining all process. The repair selection strategy is found by the Eigen values from the assigned Eigenvectors.

An optimised repair technology/process selection strategy (ORSS) for repairing aero engine components is developed. ORSS includes three modules, namely (i) Repair performance selection criteria, (ii) Experts' repair process performance selection database, and (iii) Eigenvector/AHP based optimised repair selection. In addition, MS excel® based tool also has been developed. The repair strategy has been developed after capturing the current industrial practices of aero engine OEMs. A total number of twenty interviews with repair engineer, services to engineering, repair processes experts and MRO business experts were conducted. To capture current industrial practices and challenges from repair engineers, issues interacting between the customers and repair engineering from services to engineering, processes capacities and capabilities and limitations from repair processes experts and MRO experts provided business challenges and opportunities. ORSS has been validated through a case study. The research results indicate that traditional repair processes are not classified with respect to effectiveness and efficiency for repairing the specific components and its damage mode; and therefore, do not address the requirements of repair engineers and business KPIs. The developed ORSS may help the repair engineers to identify the optimum repair process within the experts' knowledge database, and thereby enhance the quality, cost and deliverability of the repair. This contribution to the research includes: (i) repair process, (ii) classification and experts' knowledge database of repair alternatives, and (iii) development of optimised repair process selection strategy for aero engine components based on damage mode. At the end the operational efficiency and effectiveness of the repair is comprehensively discussed and novel way is proposed for describing efficiency and effectiveness in repair environment.

The information about the development of knowledge sharing framework takes overarching concept from repair optimisation and extends the requirements back to designs to achieve repair optimised design for the future. The qualitative analysis and codification of the focus group and the questionnaire findings are presented. These findings are codified as basic requirements for the knowledge sharing framework that includes; what is required from repair team, how repair team can help design to help them. The design teams provide the information on how the repair knowledge can be useful but the missing link is that the designers don't know about the repair and how repair team can update the design team on component design due to the communication gap between the teams.

To address all these aspect of knowledge sharing the seven step framework is recommended which starts from: Developing common understanding across all the teams by defining taxonomy (four levels: Engine, Commodity Component and damage-mode). On next level the list of repairs that can be carried out on the given component for the given damage. Next level the repair team list all valid repair processes for the component. After this level the repair team will report how component was deteriorated or degraded to current condition. The design team will appreciate the field data of real deterioration of component as tools like FMEA and FMECA are synonymous for the design team to assists in modelling the degradation of the component for batter understanding. Next level to this is, repair team updating the design team for the ideal repair process they would like to use for repairing for the given component with given damage and how design team can update or enable the component design. This will be the opportunity for the repair team to suggest the design update. Lastly repair team will also need to provide the business justification of these component design updates & suggestions. This chapter describes knowledge sharing in great details and provides the case study of the framework, how repair are conducted at each overhaul, how component is deteriorated and above all how design can be improved for repairing.

The ORSS framework has use three methods to validate. First, from the case study of the selected two components (Engine casing and NGV), second from the comparison of past cases which has been update due to quality, cost or delivery challenges and third from the expert focus group creating a scenario to test the

ORSS framework and assessing its performance against their knowledge. The ORSS framework is successfully validated by all recommended methods.

The developed framework was validated by case studies. These case studies were based on two different components to examine all aspects of the repair knowledge framework. These components were intentionally selected as a model of purposeful sampling. Each validation activity was a practical and qualitative survey completed by the participant to measure the framework success in sharing the repair knowledge effectively.

These results were then shared and validated by the early stage design teams facilitated by servicing for the engineering team, to examine if the suitable knowledge requirements have been discovered and gathered. The qualitative surveys were utilised in validation. The results proved that there was good success in the framework facilitating repair knowledge sharing, therefore verifying the requirements of repair knowledge sharing at early design stage. The additional work is needed to develop a framework from the design knowledge sharing to repair to create a cohesive environment in the organisation.

9.1 Research Objectives and deliverables

Predominantly the research questions have two main parts, the first deals with the optimised repair selection strategy and the second deals with the repair knowledge feedback:

Research Questions for ORSS (Optimised Repair Selection Strategy)

Research Question 1: *What are the current repair technology selection processes, strategies and what are the bottlenecks?*

Answer 1: There is no formal method for repair technology/process selection. Often the selection of this vital task is established on prior experience, traditions or biased; this approach does not encourage the improved and optimised selection.

Research Question 2: *what are the prerequisites for optimised repair selection strategy and how it can support the decision making in the repair process?*

Answer 2: It depends on many factors which are addressed in the literature review, the industrial information gathering, expert interviews, questionnaires, operational development and industrial appraisal. After many evaluations the challenges include:

Research Question 3: *Assessment criteria for the repair team for their business performances.*

Answer 3: the business performance criteria for the repair team are cost, delivery and quality.

Research Question 4: *What are the most common methods cited, applied and discussed in the literature for solving multi-criteria decision challenges which are suitable for repair technology/process selection.*

Answer 4: This deliverable is addressed in literature review chapter 3.

Research Question 5: *Which methods have been suggested for the decision making in different situations of operations management like process design?*

Answer 5: This deliverable is addressed in literature review chapter 3.

Research Question 6: *What methods are presently being employed for (multi-criteria decision making) MCDM in the similar industries.*

Answer 6: This deliverable is addressed in literature review chapter 3.

Research Question 7: *What are the industrial requirements of ORSS (optimised repair selection strategy) decision-making framework? Additional requirements will be introduced as research and the knowledge progresses.*

Answer 7: This deliverables are addressed in framework for ORSS chapter (5). The planed feature for the demonstrative tool is also given in this chapter.

Research Questions for repair knowledge sharing framework are addresses in chapter 6.

Optimised repair selection strategy brought many impact factors into light. How repair effectiveness can be translated, what is the efficiency in repair and how repair is compared with remanufacturing. The ORSS framework itself raised concern of repair processes selection and repair strategy for the components lifecycle. The repair always compared with manufacturing not remanufacturing. Analysis of real efficiency from repair to remanufacturing based on cost however the industry considers the manufacturing cost for the repair efficiency. Analysis of real effectiveness, from repair to designed life of the components based on manufacturing/remanufacturing.

It can be assumed that the correct level of knowledge is a bit ambiguous to the repair and design team members, specifically at early design stage with varying targets. It seems from the beginning that the knowledge is very subjective to each team for their specific roles. The challenges were to find the right knowledge constituents for each team. Furthermore the repair knowledge for the design becomes useful when the design is in some maturity, but contrary to make any changes at that stage, with different level of variability in effectiveness. It is possible to bring the design aim and repair targets closer together to create more cohesiveness.

There is clear evidence that the framework brings cohesion with success between the stakeholders. It can also be said that further work is needed in how much design aims can be compromised to accommodate the repair targets.

It was also emerged that the structured knowledge had the biggest impact compared to unstructured knowledge. It was understood that this was the first attempt to bring the repair knowledge sharing to design in this manner.

The given results support and validate the repair knowledge framework with great emphasis to explore the knowledge sharing aspect of the early design process with cohesion to repair teams. This validation exemplifies the importance of repair knowledge sharing to improve the design in operation, design update to save revenues and repair effectiveness and efficiency and business effectiveness. This framework could be integral part of the overall knowledge sharing strategy.

The life of the components is discussed and modelled, that can be used in knowledge sharing for the design to inform about the challenges repair team/engineer faces and how it can be addressed in the design. Components undergo many different regimes of repair based on the damage and operations of the components. Typically, there are six overhaul of the jet engine, recommended by the manufacturer (RR) hence there are six opportunities for components to get repaired.

Structured knowledge sharing framework, findings prompted the vital design updates which will make the design friendlier in the operational life of the aero engine.

Figure below describes component deterioration through its operational life

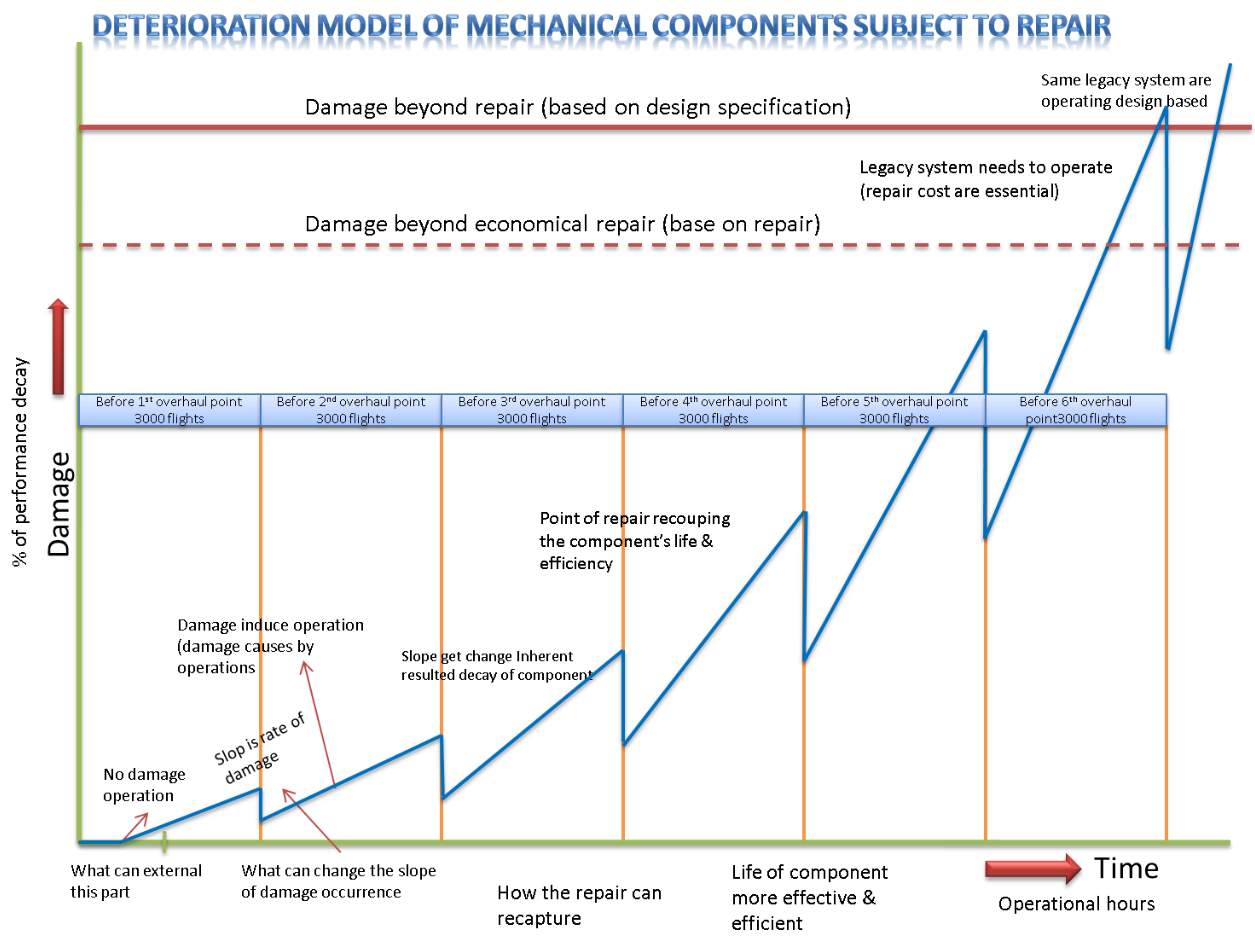


Figure 87: Component deterioration in operational life

The repair team can increase their efficiency by dealing effectively with new aero engine repair selection strategy. The future proofing of aero engine for long term competitiveness need the right technology selected for the future design, hence making the aero engine more competitive in the market.

This project offers to solve three main challenges

- Repair strategy selection
- Repair knowledge sharing for designers
- Technology selection

This research is based on the hypothesis that Multi-criteria decision making tools can aid in achieving an informed and right decision with knowledge sharing to designers that will help them to develop effective and efficient designs for the future.

Technology selection for the future engine program will keep the aero engine competitive in the market. This requires close consultation with the stakeholders and key inputs from the repair team services or the engineering repair technology teams.

9.2 System level description of the thesis

This thesis has emphasised two themes of aviation industry, one ORSS (optimised repair selection strategy) in large civil aero engine and the 2nd the repair knowledge sharing to address components design shortcoming. The following figure elucidate how ORSS and repair knowledge sharing frameworks links together and further explain each elements.

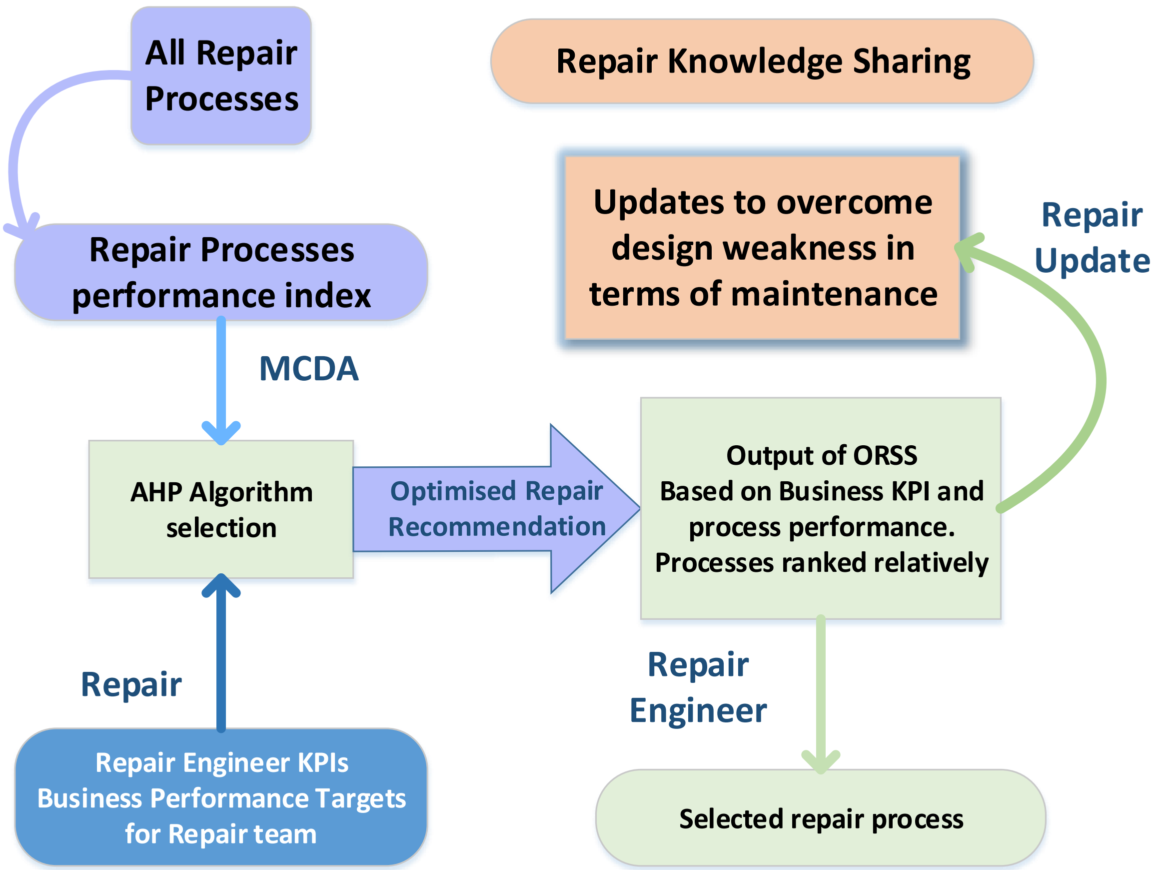


Figure: 88 System level diagram

The thesis studied to find out the bottlenecks in repair (the technique like Pareto analysis was used) in term of damages modes, components and cost/delivery. This gives the focused repair processes and components. The components and damage mode base repair processes performance index is developed. The repair engineers can emphasis required KPIs by help of MCDA (AHP) to select the best performing repair processes. The output would provide the best repair process of every repairing stage based on component and its damage mode with relative ranking of other competing repair processes. These selections are recorded and common repair processes, components and damage mode are highlight for repair focused design updates from repair team. These updates initiates 7 step repair knowledge sharing framework to support design, as portrayed in the figure 88.

The proposed frameworks have addressed most of the challenges in repair technology and knowledge sharing, which impacts on servitisation and aero engine design. There are many aspects of repair technology selection and knowledge sharing; reporting will also assist the design teams for further improvements in the aero engine design.

Furthermore, these frameworks also give the flexibility and empowerment to repair teams to prioritise future repair technology selection which can improve, repair teams key performance indicator based on business acumen.

The communication will also improve within the teams and a cohesive design will help the business improvements. The shareholder value will be maximised by implementing this knowledge sharing framework.

Chapter 10

10 CONCLUSIONS

The conclusions provide the answer to the aim of the research: Optimise Repair Strategy Selection and Repair Knowledge sharing to Support Aero Engine Design.

10.1 Optimised Repair Selection Strategy

An innovative method based on MCDA is recommended which takes business KPIs and the technical experts into account. Optimised repair selection strategy framework is expert based algorithms merged into business KPIs to support optimised repair process selection. This framework (ORSS) can also be used to assess key factor which influence the technical repairs in the aero engine components. Furthermore ORSS also provide the opportunity to manage components lifecycle repair strategy. The limitation of this framework is the experts' interpretation of business KPIs and the repair processes. The comprehensive qualitative analysis was done to identify the parameters for optimisation for repair team and its performance. The optimisation parameters were selected as efficiency and effectiveness which translated as quality cost delivery (QCD) from qualitative analysis of three different teams for the business performance. QCD were also used as the business performance targets for the repair teams. How QCD affect the repair team and how it can be used in efforts to make repair team efficient and effective was reported. The component repair experts and repair processes experts evaluated each repair process based on the component damage and expressed each repair process in QCD scores. This novel approach provided the opportunity to combine expert based QCD with the required QCD to meet the performance targets with the help of AHP based on Eigenvectors, a proven philosophy within MCDA (Multi-criteria decision analysis).

10.2 Repair effectiveness & efficiency measure

This part reported two integrated novelties, how repair efficiency and effectiveness are measured in operational environments.

The repair team were instigated further on how operational efficiency and effectiveness is measured which is very important especially in maintenance intensive environment. The method of measuring and quantifying repair efficiency and effectiveness is defined, which is based on the degradation and recapturing the remaining useful life of component. The repair of components can be easily measured by the proposed approach which compares the repaired component with manufactured component. This novel method compares the useful life recaptured by repair with actual manufactured life to examine the effectiveness and compare the cost for the efficiency of the repair. This study evaluated three components of the same kind. First was selected based on that it was not repair but degradation/deterioration was monitored. The second one was repaired with conventional methods and degradation/deterioration was monitored. The third component was repaired with best repair processes and degradation was monitored. The comparative analysis was done to measure the efficiency and effectiveness; further details are given in the chapter 5.

10.3 Repair knowledge sharing framework

This part reports the novel repair knowledge sharing framework, the most effective way to share repair knowledge with design, including potential design updates with justification.

Repair knowledge sharing framework provides the inside of the repair teams concerns to design teams for future efficient and effective design for repair. The key steps for knowledge sharing from repair to design with key design updates based on repair knowledge to supports 'Repair focus design'. The qualitative analysis of the repair teams and design teams were conducted to share the repair knowledge in design teams' desired manner. The repetitive collection and analysis of the information from the repair and design teams guided the 7 key steps for knowledge sharing framework. These key steps are the minimum yet comprehensive to disseminate the most of repair concerns with update design suggestion to design team.

10.4 Recommendation for the future work

How QCD are managed from optimised repair selection strategy for component lifecycle repair strategy development and the repair processes/technology evaluation by experts based on location.

Developing repair strategy cost estimation method focused on values needed to be addressed for competitiveness over component lifecycle repair strategy development.

Repairing quality rejects from the manufacturing of OEMs to increase effectiveness in components supply for MROs (components remanufacturing) also remanufacturing point of component from components overhauling.

- To develop a repair strategy cost estimation method focused on values needed to be addressed for competitiveness at each overhaul.
- Repairing quality rejects from the manufacturing of OEMs to increase effectiveness in components supply for MROs (components remanufacturing).
- 'Repair vs replace' based component design and vice versa.
- Remanufacturing point of component at overhauling.
- How QCD are managed through repair lifecycle and experts' evaluation for the processes according to locations
- How repair knowledge sharing can be practiced at different engine derivative designs.

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APPENDICES

Whilst Heading 1 to Heading 6 can be used to number headings in the main body of the thesis, Heading styles 7–9 have been modified specifically for lettered appendix headings with Heading 7 having the 'Appendix' prefix as shown below.

Appendix A

The example of the output for design team feedback is given as:

Table 31 Repair Knowledge feedback for cleaning process

Overhaul	Damage	Repair processes	Design Enablers	Design disablers	Notes/reasons
1st O/H	Some attrition lining damage	Cleaning	Easy access	Complex geometry	Complex geometries need more time and special processes and specialised inspection for anomalies
	Oil staining	Chemical dip tanks MEK wipes Water jet Ultrasonic	Smooth surface with less variations	Complex surface geometry	Complex surface geometries need more time and special processes harder chemical and regressive cleaning processes which can introduce fatigue into the parts (i.e. water jet cleaning)
			Corrosion resistance	Moisture resistive, Chemical resistive	Most of the cleaning is based on water based chemical
		Inspection	Free datum surfaces	No datum surfaces	Datum become variable to different repair engineers which introduce tolerance issues

			Thick and non-wearing surfaces	Thin datum surfaces Wearing datum surfaces	Thin surface distorts the tolerance Wearing surface datum increases repair time and the repair engineers need more effort to overcome repair tasks
			Real Tolerances through design life	Realistic tolerance in repair	The tolerance is different in manufacturing, services and repair
			What point design loses its function	Unrealistic/very close tolerance to the capacities	Design tolerance become very close to repair process capacities Requires more time, cost and quality issues.
			Allow more hand tool measurements		
			1st principle tool ability in inspection		

Table 32 Repair Knowledge feedback for Inspection process

Overhaul	Damage	Repair processes	Design Enablers	Design disablers	Notes/reasons
1st O/H	Some attrition lining damage	Inspection	Free datum surfaces	No datum surfaces	Datum become variable to different repair engineers which introduce tolerance issues
	Oil staining		Thick and non-wearing surfaces	Thin datum surfaces Wearing datum surfaces	Thin surface distorts the tolerance Wearing surface datum increases repair time and the repair engineers need more effort to overcome repair tasks
			Real Tolerances through design life	Realistic tolerance in repair	The tolerances are different in manufacturing, services and repair

			What point design loses its function	Unrealistic/very close tolerance to the capacities	Design tolerance become very close to repair process capacities Requires more time, cost and quality issues.
			Allow more hand tool measurements	Difficulty in measuring the feature in a design for inspection	Measuring: Flatness, roundness, roughness Measuring system needs to be calibrated each different measurement. i.e. cost , money and quality penalties in the repair
			1^{st} principle tool ability in inspection	Latest techniques requiring specific procedure,	

Table 33 repair Knowledge feedback for metal spray process

Overhaul	Damage	Repair processes	Design Enablers	Design disablers	Notes/reasons
1st O/H	Some attrition lining damage	Metal Spray	Wearing surfaces to be repaired	Extra efforts, time & cost	Understand, how next repair could be omitted
	Oil staining		Understanding the rate of wear can help repair mitigation	Decision of doing unnecessary repair	How the wearing mechanism is progressing so the repair can be focused
			Any location needing metal spray needs to be in an aspect ratio of 1:10, including wearing	Wrong aspect ratios will be difficult to repair, other repair processes will include more cost, time and induce damage to the components	Higher aspect ratio flanges will be easier to repair from metal spray. Changing the aspect ratio in operation may also make repairing difficult.

			Change to tribology to enable normal coating	Exotic coating using the process like HVOF and D-Gun	The coating like nickel-based are cheaper and easier to repair. Minimising HOVF and D-Gun can reduce repair cost significantly. Hard wearing coating
			Introduction of gasket (metal gasket) in between two wearing surfaces		There will be no need to repair many different surfaces, just a matter of changing the gaskets, saving the repair time, cost quality and longer component life.

Table 34 Repair Knowledge feedback for Painting process

Overhaul	Damage	Repair processes	Design Enablers	Design disablers	Notes/reasons
2nd O/H	Heavy attrition damage Heavy oil staining Light corrosion damage	Cleaning, Inspection, and Metal spray as above	As above	As above	As above
2nd O/H	Heavy attrition damage Heavy oil staining Light corrosion damage	Painting /repainting	Patching repair paints	Specific paint based on material, thermal condition limitation. Curing paint Difficulty in paint removing	Some paint curing temperature damages the attrition lining. Removing become cumbersome process

			Process flexible paints	A specific method of applying	Flexible paint will support, repair, if paint can be applied by brush, spraying offering process flexibility
			Less/no toxic paint	Prerequisites for the safety	Prep time become long Some location cannot use because of legislation less consistence repair globally.
			Less prerequisites of Paint	The prep for paint is costly and time consuming	E.g. If the paint can be sprayed over bolts location so, the bolts can tighten over the paint rather than masking the bolt location so no paint can be on bolt location.
			Corrosion resistive metal under the paint	Patches of paint get removed and metal under it corrodes very quickly	More corrosion resistive metal under the paint

Table 35 Repair Knowledge feedback for Machining process

Overhaul	Damage	Repair processes	Design Enablers	Design disablers	Notes/reasons
2nd O/H	Heavy attrition damage Heavy oil staining Light corrosion damage	Cleaning, Inspection, and Metal spray As above	As above	As above	As above
2nd O/H	Heavy attrition damage Heavy oil staining	Machining	Variation of surface finishes	Variation in surface finishing requires more tool and specialised tool costing and taking more time	Variation in surface require processes to take long, use more expensive tooling and more time with planning

	Light corrosion damage				
			Relaxation in surface finish	High surface requires more tooling. Cost higher and take more time in repair	Some hidden cost does not represent the true value of repair before it is completed. High rework
			Datum on non-wearing surfaces	Wearing datum increase repair work and cost with decreasing the quality	Accept the damage on datum surface, damage resistive datum
			Minimise machining	Specific machining process	
			Ability to do manual machining	Complex features to machine	Less complex features will increase the flexibility in repair from machine selection less time for complex programming, more accuracy and quality

					repair, also offering longevity in repair

Table 36 Repair Knowledge feedback for welding process

Overhaul	Damage	Repair processes	Design Enablers	Design disablers	Notes/reasons
2nd O/H	Heavy attrition damage Heavy oil staining Light corrosion damage	Cleaning, Inspection, and Metal spray Machining	As above	As above	As above
3rd O/H	Heavy attrition damage Heavy oil staining Heavy corrosion	Cleaning, Inspection, Welding			

	Light structural	H/T Repainting Machining			
		Welding	Tolerance in distortion	Tight tolerance in distortion	
			Increasing fatigue penalties	Tight fatigue penalties	
			Material which has less effect of Residual stress	Residual stress	
			Weakening of metal	Prone to weakness	
			Changing material properties	Changing material properties	

			Non-structural process		

Appendix B