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Development of a Repair Technology Selection Tool for Aerospace Components

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SOMMARIO

Negli ultimi anni sono state sviluppate nuove soluzioni di tipo end-life per prodotti. In particolare, ci sono opzioni di riutilizzo a recupero di valore aggiunto e opzioni di recupero dei materiali. Tuttavia di solito la selezione di tecniche di riparazione, fatta da operatori, non è ottimale, in quanto si tratta di un problema decisionale complesso a causa della presenza di diversi criteri contrastanti, quindi vi è la necessità di uno strumento o tool che aiuti il processo decisionale. La prima fase della presente tesi è iniziata con una ricerca sullo stato dell'arte della teoria del Remanufacturing e delle tecniche MDCM, per identificare il gap nella letteratura. Una volta Identificato il gap, è stato sviluppato un framework ed un algoritmo decisionale integrato basato su Fuzzy AHP e TOPSIS. Questi ultimi due metodi sono alla base del programma software sviluppato tramite Microsoft®Excel VBA. Attraverso il case study, il programma e il suo algoritmo è stato testato e validato da un esperto in collaborazione con Rolls Royce plc. Questa tesi si propone di aggiungere alla letteratura un esempio di tool per la selezione di tecniche di riparazione per ogni fase del processo di riparazione. Tuttavia, questo può essere anche usato come primo passo per lo sviluppo di altri tool in altri settori o nello sviluppo di programmi che prendano in considerazione più criteri.

ABSTRACT

In the last years new end life solutions have been developed for products. In particular there are value-added recovery reuse options, and material recovery options. However usually the selection of repair technique, done by operators, is not optimal as it is a complex decision making problem and it needs to consider several different and contrasting criteria, hence there is a need of a tool that aids the decision making process. The first stage of the thesis started with a significant research review on Remanufacturing and MDCM techniques, in order to identify the gap in literature. From the identified gap, a decision making framework and algorithm based on Fuzzy AHP and TOPSIS was developed, that is the basis of the software tool created through Microsoft ® Excel VBA. Through the case study, the tool and its algorithm has been tested and validated by an expert in collaboration with Rolls Royce plc. This thesis adds to the literature an example of tool that helps the selection of repair techniques for each stages of the repair process. However this can also be used as first step for developing other tools in other fields or in tools that take in account more criteria.

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LIST OF ABBREVIATIONS

MCDM	Multi Criteria Decision Making
AHP	Analytic Hierarchy Process
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
PSS	Product Service System
DM	Decision Making

1 INTRODUCTION

1.1 BACKGROUND

In the last years, new end life solutions have been developed. Some of the most used end life solutions are the reuse alternatives, which consist of value added recovery solutions, like repair and remanufacture, and material recovery options, like recycling (Thierry et al., 1995). However the idea of product reuse is not new, as it has been an ordinary industrial routine since the 1940s (Hatcher, Ijomah and Windmill, 2011).

The product reuse industry got indeed a boost during the Second World War when many manufacturing facilities changed from ordinary production to military production, and therefore the products in use were to a large extent remanufactured in order to keep society running. The industry sector that has the most experience in the product reuse area is the automotive industry. However, the concept of new end life solutions has spread during the latest decades to other sectors, such as those dealing with electrical apparatus, toner cartridges, household appliances, machinery, and mobile phones.

Figure 1-1 shows some of the currently most used closed loops or reuse options.

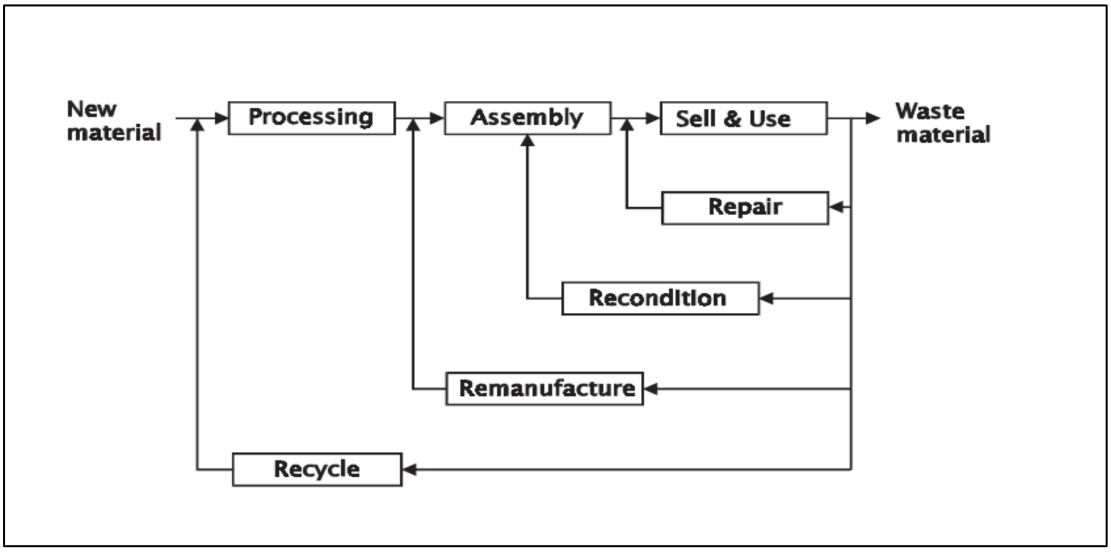


Figure 1-1 Closed loop design through repair, remanufacturing or recycling (King et al., 2006)

In Figure 1-1 it is moreover possible to see how different reuse options feed a generic production process.

In general the primary objectives of product reuse can be synthesised in the reduction of the quantities of waste, recovering in this way the economic, product reuse enables 30-40% lower production costs (Mukherjee and Mondal, 2009), and the ecological value of used products (Thierry et al., 1995). Moreover the current yearly reuse market revenues have been estimated as $100 billion in the USA (Stock, Speh, and Shear, 2002).

In Figure 1-2 it is possible to see how the flow of returned products is managed and the amount of money that can be recovered.

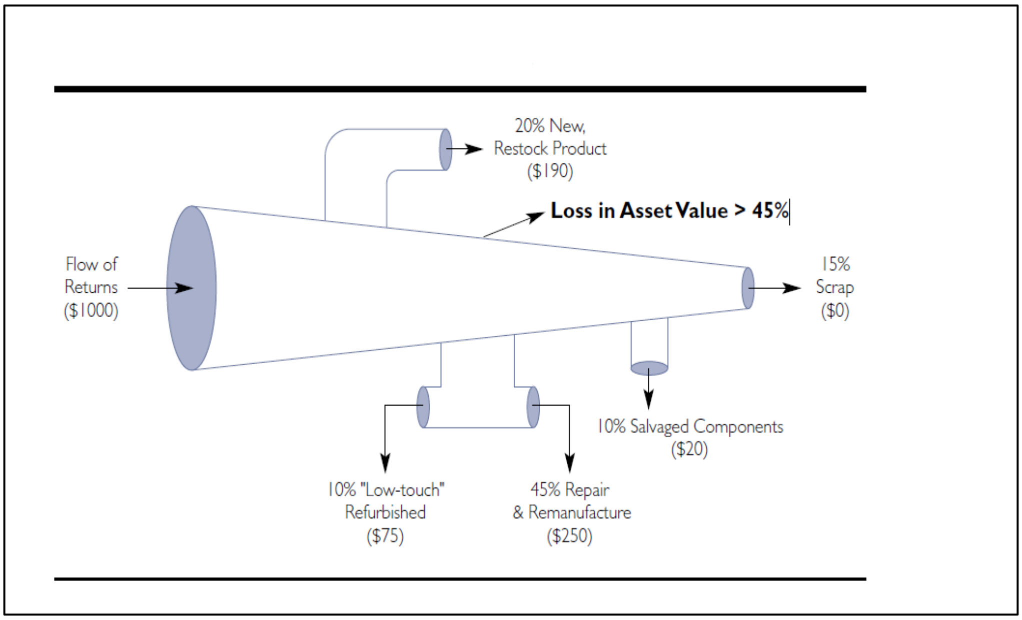


Figure 1-2 Shrinking pipeline for product return (Blackburn et al., 2004).

The benefits of product reuse are not nevertheless just economic, but also environmental and social (Feng, 2011).

Indeed compared with the production of new products, in this case there is also use of less energy (Lund, 1984; Giuntini and Gaudette, 2003), and additionally in matter of environment, the legislation in Europe is becoming increasingly strict (Guide et al., 2003).

In fact in January 2003, the European Union issued a directive called Waste Electronic and Electrical Equipment (EU-WEEE, 2003). The aim of this directive is primarily to prevent the accumulation of waste containing electrical and electronic products, and at the same time promote reuse and material recycling.

In regard to the focus of the thesis, the aerospace sector, the high-value and high-tech attribute of airplane components furnish a noteworthy economic potential for product reuse savings, as the costs related with producing new components are relatively high. And the fact that most manufacturers, including Rolls-Royce and General Electric, have already adopted a system, Product Service System or PSS, that permits the exploitation of product reuse benefits (Feng, 2011), can be used as evidence of the convenience of product reuse.

Between all the reuse options, repair, merely the correction of determined faults in an object, is considered the simplest and most logical method to close the product reuse loop and to increase the product life. Anyhow, while this is inherently an elementary idea, interestingly the practice of repairing in industry is relatively low, and relatively low research has been done in literature in order to comprehend this closed loop solution (King et al., 2006). And for this reason repair has been selected as specific reuse option of this thesis.

Furthermore the selection of the best repair technique for a certain repair process is a complex decision making problem with several parameters to take in account, hence the need to create an algorithm that facilitates the decision making process. In literature several algorithms can be found for the reuse options (Zhao et al., 2014; Flapper, Gayon and Lim, 2014; Bulmus, Zhu and Teunter, 2014), but these algorithms focus mainly on solving the problem of whether a product should be repaired or replaced and not on the selection of the specific repair method. However also if some rare exceptions exist (Wang, 2013), the focus is not on the repair process.

Moreover the need of decision making tools is highlighted by the fact that people in the repair field usually select techniques based on their past experiences, hence far from optimal solutions. This will generate therefore higher costs and repair times, lower repair quality and the consequent increase of wastes.

So as in literature there is no focus on the development of a tool and a decision making algorithm for the repairing process, a repair technology selection tool which could provide an evaluation of the repair techniques for each stage of the repair process, is needed, in order to provide help in the decision making process.

1.2 THESIS STRUCTURE

This thesis paper consists of 10 chapters.

- Chapter 1 is an Introduction to the topic
- Chapter 2 is the Literature review, to analyse the topics related with the thesis.
- Chapter 3 are the Aim and Objectives of the thesis work.
- Chapter 4 is the Materials and Methods used during the project.
- Chapter 5 is the description of the Developed Decision Making Algorithm with its parts: Assumptions, Framework, Selection of Criteria, Fuzzy AHP logic, Linguistic scales, Creation of weights and ranks.
- Chapter 6 is how the algorithm has been implemented on Microsoft Excel
- Chapter 7 is the description of the component chosen and analysed
- Chapter 8 is the case study.
- Chapter 9 is the discussion.
- Chapter 10 is the conclusions.

2 LITERATURE REVIEW

The first stage of the project work was to do a research review in order to identify possible gaps and to improve and enhance the understanding of the writer in the field of MCDM and Repair technologies. This research process was also needed in order to identify the research gap this paper aimed to fill up. The present study was carried out using papers and books, from academic databases and search engines, as Springer, IEEE Xplore, Microsoft Academic Search, Scopus, Google Scholar and Sciencedirect, from the library in Cranfield and from the biggest aerospace engine manufacturers' websites, like GE, Rolls Royce, and Pratt & Whitney.

The research strategy used, started with the identification and the definition of keywords and was followed by a review of the defined keywords, in order to have a deeper knowledge in that particular field. Some of the initial keywords that were subject to research are MCDM, Decision Making, Remanufacturing, Repair-Stages. Once a more complete knowledge of a certain topic was reached, more detailed researches were done with more specific keywords, e.g. Fuzzy AHP, TOPSIS, ranking methods, evaluation scales, failure modes for NGV, in the sources listed before. In addition the contribution of academia experts, doing similar researches, was used in order to obtain several papers on advantages and drawbacks of MCDM.

The following chapters of this paper are listed in the disposition followed by the research process. The first chapter describes what remanufacturing and repair are, and what their uses in industry are. Then the focus is shifted on the MCDM methods with an analysis of the difference between techniques. The third chapter is about the method used to produce weights, the Fuzzy-AHP, with an introduction on AHP. The fourth chapter is about the ranking systems used, the TOPSIS. Finally in the last chapter the knowledge gap that has been identified and that is the motivation of the thesis itself is explained.

2.1 USE OF REMANUFACTURING AND REPAIR IN INDUSTRY

Between all the value added recovery solutions introduced in the background chapter the best known and the most studied in the last years is Remanufacturing. In literature there are several definitions of remanufacturing (Majumder and Groenevelt, 2001; Lund, 1984; BSI), and shortly it can described as a process with the aim of recovering used products and of returning them to performances similar to original ones. The process itself, which characterises remanufacturing, can be described as formed by disassembly of used items, inspection, repairing of the components, and the reuse of the parts in new product manufacture (Majumder and Groenevelt, 2001).

Interestingly there have been also several researches, in the field of remanufacturing, that show all the economic benefits and costs savings that the approach brings to companies of all dimensions, from the small ones (Gray and Charter, 2007) to the bigger ones, as GE (Statham, 2006).

The remanufacturing market itself offer great opportunities to interested businesses, as by the end of the 1990s the total aggregate revenues for remanufacturing companies in the USA were equal to $53 billion (Lund 1998). While in the UK, the remanufacturing industry has been estimated as a £5 billion industry per year (OHL, 2004).

With regard to this paper it is interesting to highlight how the repair process fits in the product reuse and remanufacturing world.

Indeed repair has traditionally been considered a constituent element of remanufacturing (Sundin, 2005). Nonetheless more recent studies have designated repair as an independent recovery option (Sundin, 2005), so it is interesting to understand better what repair is.

In general the aim of all repair processes is to restore damaged products to normal working conditions. Furthermore the focus in a repair process is usually on fixing and replacing not working parts, while the functioning parts are not affected to analysis. (Thierry et al., 1995)

However as over time all systems deteriorate, repair is a process that is necessary. In point of fact when the deterioration has reached a critical level (Hayre, 1983) the manufacturer has to decide between two options: repair the failed part or replace it with a new one (Iskandar and Murthy, 2003). Normally the first option is less expensive than the second option (Iskandar, Murthy and Jack, 2005)

The choice between the two options depends, considering a basic level analysis, on the comparison between the cost of repairing a component with the cost of replacing the component with a new one (Iskandar and Murthy, 2003). Anyhow the decision is often far more complex than just cost analysis, as it has to take in consideration also availability, performance and the possibility of future failures (Yung and Bonnett, 2004). A possible decision process is shown in Figure 2-1.

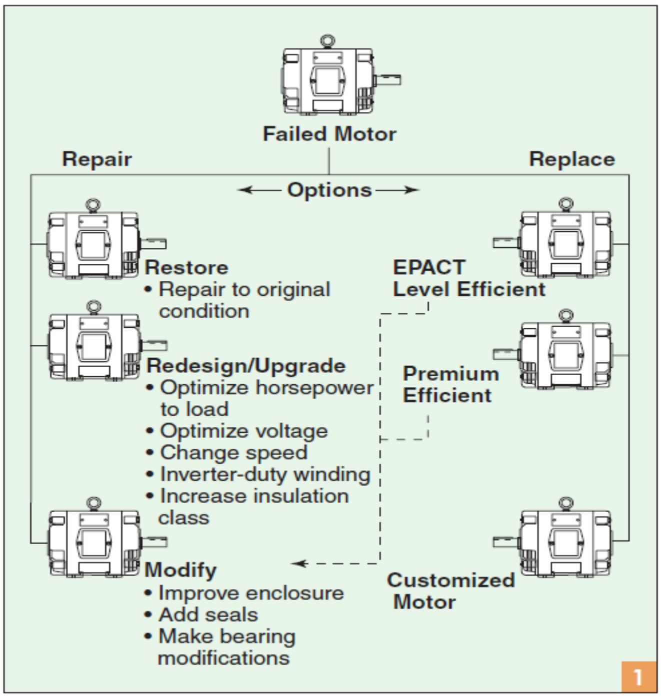


Figure 2-1 General decision process for repairing or replacing an engine (Yung and Bonnett, 2004)

Anyway there is not a mutual agreement in literature on whether once repaired items have performances close to the normal working standards or not. In fact some papers argues that the repaired products have lower quality standards than new ones (Thierry et al., 1995), or that they are in a state that is acceptable but not as good as a new one (Hayre, 1983)

But on the other hand, the majority of the opinions in literature are that a failed system after repair will have the same level of reliability of a new one, or the identical failure rate as it had in the instant before of the last failure (Lai et al., 2000).

Regarding the specific sector of this paper, the aerospace industry, an engine can be installed on an aircraft for a limited maximum time, which is a fixed period agreed between the engine producer and the airworthiness authority (Rolls Royce plc, 1996). Moreover the lives of most of the components of a gas turbine are limited if compared to the life considered useful for an aero engine (Pallos, 2001; Álvarez Tejedor, Singh and Pilidis, 2013). So continuously decisions are taken regarding the replacement or the repair of a component (Pallos, 2001).

In particular between the two, repair is the most selected option, because of the high cost for producing or buying a new engine and for the fact that engine users usually try to keep the amount of spare engines owned to a low minimum. So already in the design stage of the production process of an engine, it is important that also the service maintaining costs are considered. That means that in the design stage all the aspects of engine reparability have to be considered, in order to reduce the repair requirements and in order to design the engine in a way it is not just easy to repair but also quickly and cheaply (Rolls Royce plc, 1996).

Latest studies show that the modular construction of engines helps cost savings and the repair process, indeed a single module, while it is repaired, can be replaced by another module and the engine returned to service with short delay (Rolls Royce plc, 1996).

Furthermore for aerospace companies, in the literature there are suggestions to institute a permanent component repair program that permits to minimise maintenance costs and permits to enhance the equipment availability (Pallos, 2001).

So from literature it can be inferred what are the advantages and the disadvantages in repairing an engine or its components, and in general the usefulness of applying a repair system or a product reuse system in industry. Once defined why it is important to apply these systems it is important to define a method that helps the evaluation of what repair technique shall be used. So in next paragraph there is a review about decision making techniques that can be used in order to develop a tool.

2.2 MCDM

The following step of the research was the analysis of decision making methods.

The term multiple criteria decision making (MCDM) refers to a situation where it is necessary to make decisions in presence of multiple and conflicting criteria (Wolf and Hötzl, 2011). In order to solve this kind of problems several methods have been proposed, which can be found in taxonomies and catalogues (MacCrimmon, 1973; Denpontin et al., 1983). Generally MCDM problems are commonly divided, according to the domain of numbers in which the options range, in two groups: the continuous or the discrete (Zanakis et al., 1998). In this paper discrete are used.

Anyhow there are criticisms to MCDM. A major criticism to MDCM techniques, which is arisen in some papers, is that different techniques, although under the same assumptions, may give different results when employed in the same problem (Gershon and Duckstein, 1983). This inconsistency in results occurs for mainly 4 reasons (Zanakis et al., 1998). Firstly the weights are used differently in the techniques. Secondly the approaches with which algorithms select the optimising solution differ between MCDM methods. Thirdly, the already chosen weights might be modified by the algorithms while attempting to achieve the objectives. Lastly some algorithms may add new parameters that might modify the process of choosing the solution.

In any case, most researchers have agreed and have argued, differently than the ones listed before, that the final solutions, of a specific problem, obtained through the use of different

MCDM techniques, are basically the same (Belton, 1986; Timmermans et al., 1989; Karni et al., 1990; Goicoechea et al., 1992; Olson et al., 1995), or that on the average the results of the methods are more or less the same also if the weights differ (Schoemaker and Waid, 1982).

In the years several schools of thought have developed for solving MCDM problems. A bibliometric study showing the development of MDCM problems over time is present in literature (Bragge et al., 2010). In the following list is possible to see an overview of different schools of thought:

1. Multiple objective mathematical programming school.

   This school of thoughts can be divided in two typologies: Vector maximisation and Interactive programming.

   i) Vector maximisation: it was originally developed for Multiple Objective Linear Programming problems. The purpose is to approximate the nondominated set (Evans and Steuer, 1973; Yu and Zeleny, 1975).
   ii) Interactive programming: In this case no explicit knowledge of the DM's value function is assumed so phases of computation alternate with phases of decision-making (Benayoun et al., 1971; Geoffrion, Dyer and Feinberg, 1972; Zionts and Wallenius, 1976; Korhonen and Wallenius, 1988).

2. Goal programming school

The purpose is to set target values for goals, and to minimise weighted deviations from these goals (Charnes and Cooper, 1961).

3. Fuzzy-set theorists

It is s an extension of the classical notion of sets. This idea is used in many MCDM algorithms to model and solve fuzzy problems (Zadeh, 1965).

4. Multiattribute utility theorists

Multiattribute utility are used to identify the most preferred alternative or to rank order the alternatives(Keeney and Raiffa, 1976).

5. French school

The French school focuses on decision aiding, in particular the ELECTRE family of outranking methods that originated in France during the mid-1960s(Roy, 1968).

6. Evolutionary multiobjective optimization school (EMO)

EMO algorithms start with an initial population, and update it by using processes designed to mimic natural survival-of-the-fittest principles and genetic variation operators to improve the average population from one generation to the next. The goal is to converge to a population of solutions which represent the nondominated set (Schaffer, 1984; Srinivas and Deb, 1994).

7. Analytic hierarchy process (AHP)

The decision-maker evaluates the relative importance of its various elements by pairwise comparisons. The AHP converts these evaluations to numerical values (weights or priorities), which are used to calculate a score for each alternative (Saaty, 1980).

In this thesis work no particular school of thoughts has been selected but a hybrid school of thought has been used, where elements of AHP and fuzzy sets has been used.

In literature it has been possible moreover to find also a taxonomy of the most used MCDM, that have been listed here:

- Aggregated Indices Randomization Method (AIRM)
- Analytic hierarchy process (AHP)
- Analytic network process (ANP)
- Best worst method (BWM)
- Characteristic Objects METhod (COMET)
- Data envelopment analysis
- Decision EXpert (DEX)

- Disaggregation – Aggregation Approaches
- Dominance-based rough set approach (DRSA)
- ELECTRE (Outranking)
- Evidential reasoning approach (ER)
- Goal programming
- Grey relational analysis (GRA)
- Inner product of vectors (IPV)
- Measuring Attractiveness by a categorical Based Evaluation Technique (MACBETH)
- Multi-Attribute Global Inference of Quality (MAGIQ)
- Multi-attribute utility theory (MAUT)
- Multi-attribute value theory (MAVT)
- New Approach to Appraisal (NATA)
- Nonstructural Fuzzy Decision Support System (NSFDSS)
- Potentially all pairwise rankings of all possible alternatives (PAPRIKA)
- PROMETHEE
- Superiority and inferiority ranking method (SIR method)
- Technique for the Order of Prioritisation by Similarity to Ideal Solution (TOPSIS)
- Value analysis (VA)

- Value engineering (VE)
- VIKOR method
- Fuzzy VIKOR method
- Weighted product model (WPM)
- Weighted sum model (WSM)

For the purpose of this paper it is interesting that some authors, instead of searching similarities between methods or between results of different methods, have instead focused on how to select the best MCDM method for a given problem (Hwang and Yoon, 1981; Hobbs, 1986; Ozernoy, 1987; Ozernoy, 1992; Zanakis et al., 1998).

These classifications, obtained through highlighting the difference in techniques inputs, are often more used as a tool for eliminating unsuitable methods rather than selecting the best method (Zanakis et al., 1998).

One possible key criterion to choose the most suitable method for a problem, as suggested by some authors, is the validity of a method (Hobbs et al., 1992). For validity of a method, it is meant that the technique produces with high probability choices that precisely correspond to the values decided by the user (Hobbs et al., 1992).

Anyhow the process to determine validity has no unique, unconditioned and actual standard and there can be contradictions in the preferences when formulated in different ways. So researchers have suggested that validity can be determined through the verification of the methods' prediction capacity on unaided decisions; not considering in this way opinions and judgements expressed for fitting the model (Schoemaker and Waid, 1982; Currim and Sarin, 1984; Zanakis et al., 1998).

Finally it is interesting to underline that researches with the aim of integrating decision making techniques are limited in number (Zanakis et al., 1998). This last consideration is important, as this paper adds to the literature an integrated multi-criteria method. The 2 integrated methods, that have been selected, are described in the next paragraphs.

2.3 AHP AND FUZZY AHP

Between all MCDM methods, the most used technique in literature, and one of the ones used in this paper, is the Analytic Hierarchy Process (AHP). Indeed this technique has found application in several applied decision making problems with successful results (Saaty R., 1987).

This technique produces, from positive reciprocal matrices through paired comparisons of the criteria analysed, ratio scale priority vectors (Saaty T, 1990; Saaty T. and Hu, 1998). Another feature of this method is that it is able to decompose a complex problem into a series of sublevel problems that are connected through a multi-level hierarchical structure. This decomposition might help the user to evaluate parameters in a more systematic way (Turgut et al., 2011). The hierarchical structure, that is created, includes elements that might be compared, like objectives, criteria, sub-criteria and alternatives of the MCDM problem.

The weights, used for the decision making process, are created through the eigenvector of a pairwise comparison matrix of these elements (Saaty T., 1977).

So AHP methodology works through a comparison system. In general cognitive psychologists have defined two typologies of comparisons, absolute and relative. In the first kind, the alternatives are compared with a proper standard that has been developed through personal experience. In the second kind the alternatives are compared in pairs according to a common characteristic. The AHP method has been used with both kinds of comparisons (Saaty R., 1987).

In spite of its popularity, AHP has however received several criticisms due to the inability of the technique itself in managing the uncertainty and imprecisions of MCDM problems (Saaty R., 1987) and for its shortcomings (Yang and Chen, 2004). In the following points, there are listed some of the shortcomings (Yang and Chen, 2004):

- The technique has found mostly application in nearly crisp decision problems;
- The scale of judgement that is created and dealt by the technique is very unbalanced;
- Human judgment associated to a number brings uncertainty to the model, and this is not considered by the technique;
- The subjective judgments, opinions and preferences of the users make the ranking rather imprecise as they have a remarkable influence on the AHP.

To overcome the previous listed issues and in order to reduce the uncertainty in MCDM problems, researchers have added and integrated fuzzy set theory with AHP (Yang and Chen, 2004). The most used are the triangular fuzzy values (van Laarhoven and Pedrycz, 1983; Chang, 1996). It is anyhow interesting to highlight that other experts have used instead the more complex trapezoidal membership functions (Buckley, 1985).

The fuzzy numbers used for fuzzy AHP are taken from the fuzzy sets theory. Furthermore fuzzy sets are normal sets whose constituents contain levels or degrees of membership (the scale of fuzzy numbers). Interestingly the fuzzy sets have been presented in literature as an expansion of the concept of set (Zadeh, 1965), and in set theory, the membership of constituents in a set is rated in a binary way following bivalent conditions, so a constituent either is a part of the set or it is not (Wu and Lee, 2007).

With regard to the triangular fuzzy numbers that are used in this paper, it is possible to say that a fuzzy number $\tilde{F}$ on $\mathbb{R}$ in order to be a Triangular Fuzzy Number(TFN) needs that its membership function $\mu_{\tilde{F}}(x): \mathbb{R} \rightarrow [0,1]$ is equal to the following (2-1) (Sun, 2010):

$$\mu_{\tilde{F}}(x) = \begin{cases} (x-l)/(m-l), & l \leq x \leq m \\ (u-x)/(u-m), & m \leq x \leq u \\ 0, & otherwise \end{cases} \qquad \textbf{(2-1)}$$

Where in the equation (2-1) **l** and **u** are the lower and upper boundaries of the fuzzy number $\tilde{F}$, and **m** is the modal value(Sun, 2010) for $\tilde{F}$ as in Figure 2-2.

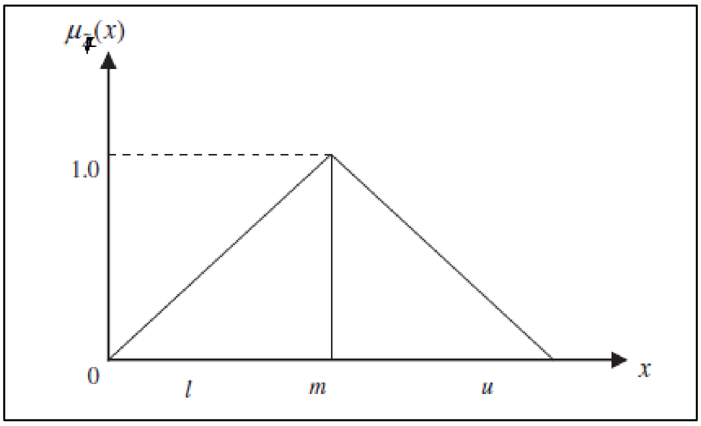


Figure 2-2 Representation of a triangular number as function of the membership function (Sun 2010)

So a TFN can be described with this set $\widetilde{F}$ = (l,m,u)

Interesting for this project, is also to see how linguistic terms are related with fuzzy numbers. In general linguistic terms are subjective types for variables of linguistic kind (i.e. sentences or words). Linguistic variables can be represented with a set of linguistic terms. So as it can be considered as a set, it will have a membership function determined through 3 values of a triangular fuzzy number with symmetric shape, the lower value, the middle value, and the upper value of the defined function range.(Sun, 2010)

From the fuzzy values in order to have a sole solution it is necessary to de-fuzzy the values, for obtain the de-fuzzy value a Best Non Fuzzy Performance or BNP (Chiu et al., 2006) can be used.

2.4 TOPSIS

The other method used in the integrated algorithm and another one of the most used techniques used to solve a decision making problem is TOPSIS or Technique for Preference by Similarity to the Ideal Solution (Hwang and Yoon, 1981) which is a technique that ranks alternatives by similarity or closeness to an ideal solution. The ranking of the alternatives is obtained by introducing a positive ideal and negative ideal point and measuring the distance of the each of the alternatives from the positive ideal and the negative ideal values (Wang & Chang, 2007; Sun 2010; Jahantigh, Hosseinzadeh Lot and Moghaddas, 2013).

The essential presupposition of the technique is that the alternative ranked as best should have the smallest Euclidean distance (Chiu et al., 2006) from the positive ideal solution

$$S_i^+ = \left[\sum \left(r_{ij} - r_j^+\right)^2\right]^{1/2} \qquad \textbf{(2-2)}$$

With r_j^+ constituted of the best value for each criteria/attribute/parameter irrespective of the alternative itself. And it should have also the farthest distance from the negative ideal solution

$$S_i^- = \left[\sum \left(r_{ij} - r_j^-\right)^2\right]^{1/2} \qquad \textbf{(2-3)}$$

with r_j^- constituted of the worst value for each criteria/attribute/parameter.

The alternative that has the highest relative closeness measurement to the positive ideal, is chosen and ranked as best. This is done through the similarity index s_{iw} to the worst condition (the reciprocal is the best condition):

$$s_{iw} = S_i^+ / (S_i^+ + S_i^-) \tag{2-4}$$

Where $s_{iw} = 0$ if the alternative has only the best performances between the alternatives and where $s_{iw} = 1$ if the alternative has only the worst performances between the alternatives (Zanakis et al., 1998).

2.5 KNOWLEDGE GAP

So through the literature review it has been possible to identify the research gap or the problem which this paper will try to find a solution to. In general in previous researches, there has not been a great focus on the repairing (King et al., 2006). Additionally there has not been a focus on developing a tool and a decision making method just for the repairing process, an algorithm that is able to analyse and propose for each step or stage of the repair process what is the best technique to use according to the failure mode that interest the component.

So the focus in this paper will not be placed on remanufacturing but on repair technologies and repair processes/stages.

Finally the development of a selection method which could provide an evaluation of the repair techniques, is needed, in order to provide help in the decision making process.

3 AIM AND OBJECTIVES

The aim of the thesis work and research is to develop a decision making algorithm and tool in order to support the evaluation and the selection of repairing techniques for each stage of the repairing process for components of an aero engine.

The following objectives were selected:

Table 3-1 Objectives

1	Determine the decision making technique that best helps to evaluate and select the best repair technique.
2	Determine the criteria that best represent the needs of the decision taking person.
3	Research in literature different failure modes (in particular of the nozzle guide vanes)
4	Research in literature different repair methods for the selected failure modes
5	Demonstrate and validate the decision tool with nozzle guide vanes case studies
6	Create a repair selection tool that works in a one-customisable user friendly software environment

4 MATERIALS AND METHODS

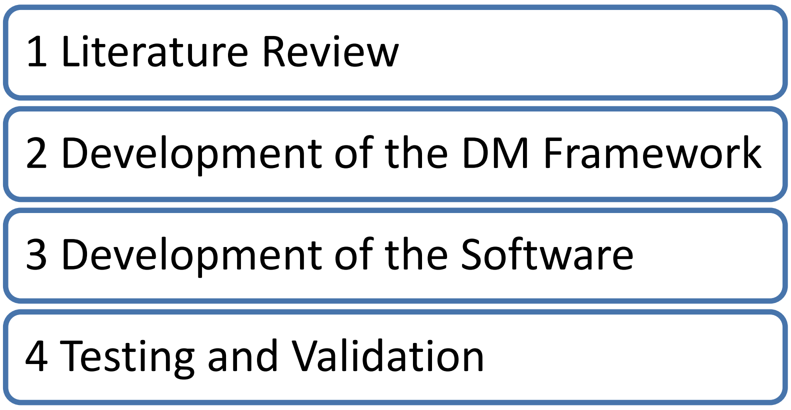


Figure 4-1 Synthetic Methodology

As it can be seen in Figure 4-1, this thesis work can be divided in 4 phases. The first extensive phase was focused on research review in the literature, in order to have a complete understanding of the topics and the research area. This part was started through the analysis of the theory of Remanufacturing, to have a general understanding of closed loop and end-life strategies; it then focused on several different decision making algorithms or MCDM. In particular in the MCDM techniques' review the centre of attention was on the benefits and on the drawbacks of each of the techniques. Finally the research review focused on failure modes, repair techniques and technologies for the selected component and for the case study under analysis. This research review was used define the research gap, and through the gap decide what were the necessities and how the tool should be developed.

The second phase was the development of a decision making framework, with all its logics, its algorithm, and its parts. In order to define the best technique for the paper in question, several MCDM case studies from literature were read. In addition suggestions and opinions from some experts were also kept under consideration.

The third phase was the development of the software through Microsoft ® Excel VBA, in this case in order to produce the software, several descriptions on how to create an Excel VBA tool were read. Suggestions from experts were also considered.

The fourth and last phase was an analysis of the functionality of the software and of the algorithm through the selected case studies. The choice of the topic of the case studies was made after consulting an expert working on a project with Rolls-Royce.

In order to assess the repair techniques performance on the selected criteria, suggestions and judgments from an expert, directly connected to industry and with a similar research project with Rolls Royce, were adopted. Moreover in order to validate and to get a feedback for the software this was shown in front of an expert that had worked on developing a similar decision making software. However due to the presence of confidentiality issues it hasn't been possible to get more information from industry. So most of the data has been collected from literature and validated by the work of an expert. Anyhow the tool is developed in a way that future user might be able to auto-validate the values through the opinion of 5 experts, in order to have a realistic validation of the different repair techniques performance.

How the project objectives were achieved is show in the following .

Table 4-1.

Table 4-1 Objectives and Tasks

OBJECTIVES	TASKS
Determine a decision making technique	1. Research in Literature to identify different MCDM techniques. 2. Evaluate the different techniques for the tool. 3. Select the best technique for the aim.
Determine the criteria	1. Research in Literature about criteria 2. Evaluate the different criteria for the tool. 3. Select the best criteria for the purpose of the paper.
Research in literature different failure modes	1. Research review to identify different failure modes. 2. List the failure modes that influence the case study
Research in literature different repair methods	1. Research review to identify different repair methods. 2. List the repair methods that influence the case study
Demonstrate and validate the decision making algorithm	1. Case Study 2. Validation through indirect data from industry
Create a customisable one-software repair selection tool	1. Implement tool in the software with Microsoft Excel®

5 DECISION MAKING ALGORITHM DEVELOPMENT

The selection of the best repair technology according to selected criteria is a multi-criteria decision making (MCDM) problem. For the purpose of this paper the decision making algorithm, that has been selected, uses not just one method but a combination of two, in order to exploit the advantages of both methods.

This decision has been taken after evaluating and reading about several methods in literature, like AHP, TOPSIS, ELECTRE, VIKOR and PROMETHEE.

The combination considered is a combined Fuzzy AHP and TOPSIS method, where the Fuzzy AHP is used for creating the weights of the criteria, and the TOPSIS is used as ranking system.

Similar approaches (but with Fuzzy TOPSIS instead of normal TOPSIS) can be found applied in different fields (Chiu et al., 2006; Sun, 2010; Torfi, Farahani and Rezapour, 2010; Rao, 2013) but not for selection of repair techniques and selection of techniques in general.

The reasons because it has been decided to use this combination of techniques are several. First of all, AHP is the most widely used method due to its well-known advantages, but instead of using a simple AHP it has been decided to use a Fuzzy AHP. This is because fuzzy logic express and replicates, as described in literature, better human thoughts than what normal numbers do. The TOPSIS method has been selected for ranking purpose because it gives additional information respect to the weighted sum that is usually used at the end of AHP. Indeed even if AHP is optimal in producing weights and usually weighted sum is taken as decision factor, the TOPSIS ranks the possible options through an index that is the closeness to the ideal solution, instead of the alternative that has the highest weighted sum. This method allows two additional facts. The first one is the closeness to the positive ideal solution; the second one is the remoteness from the worse solution. That means that not only the best alternative is received back from the rank but also a distance from the two extreme situations. This information is indeed important in order to have a better understanding on how the alternatives differ, and the information shows how far they are from each other. Interesting is that in this way it is possible to understand if the best ranked solution is in this position because it is the farthest from the worse one, or because it's the closest to the best one. In addition if the alternatives have a similar index of closeness, it means that the difference between them is not too significant. While a relevant difference in the value of the index of closeness mean that one alternative is far more preferable than the other.

In any case as showed in the literature review several authors claim that the final results of the MCDM methods are the same or at least similar, so the main reason for the use of this combination is the additional information you receivable from this integration.

In the next paragraphs it will be described in detail the assumptions, framework, the criteria, the fuzzy AHP logic used, the weights creation and the ranking system of the tool developed.

5.1 ASSUMPTIONS

Here are listed the assumptions considered in the development of the algorithm and tool. The reason because these assumptions were established, is to make the development of the complex algorithm more feasible and make the software more performing.

- Repair is committed, the first inspection has already been done (it is considered as a pre-repair phase), so the decision to repair has already been taken, the scope of the tool is indeed not evaluate if repair or replace but to evaluate which repair techniques to use.
- The failure or damage modes considered are the most common for NGVs, found through literature, other failure modes for aero engine will be listed however but not used for the algorithm
- For each stage of the repair process just the top three repair techniques will be considered, the selection of the three has been done after research in literature and after suggestions of an expert.

5.2 DECISION MAKING ALGORITHM FRAMEWORK

In general all the repair processes starts with the decision whether repair or replace a damaged component. However as in literature there are several studies on this part, the aim of the algorithm developed here is different and will instead, as stated in the assumptions focus in the selection of the repair techniques. This is mainly done because the decision of repairing or not is a pre-repair phase, and not a repair phase. So here the process starts with the cleaning instead of the inspection process.

The figure in the following page will help in the understanding of the decision making algorithm framework.

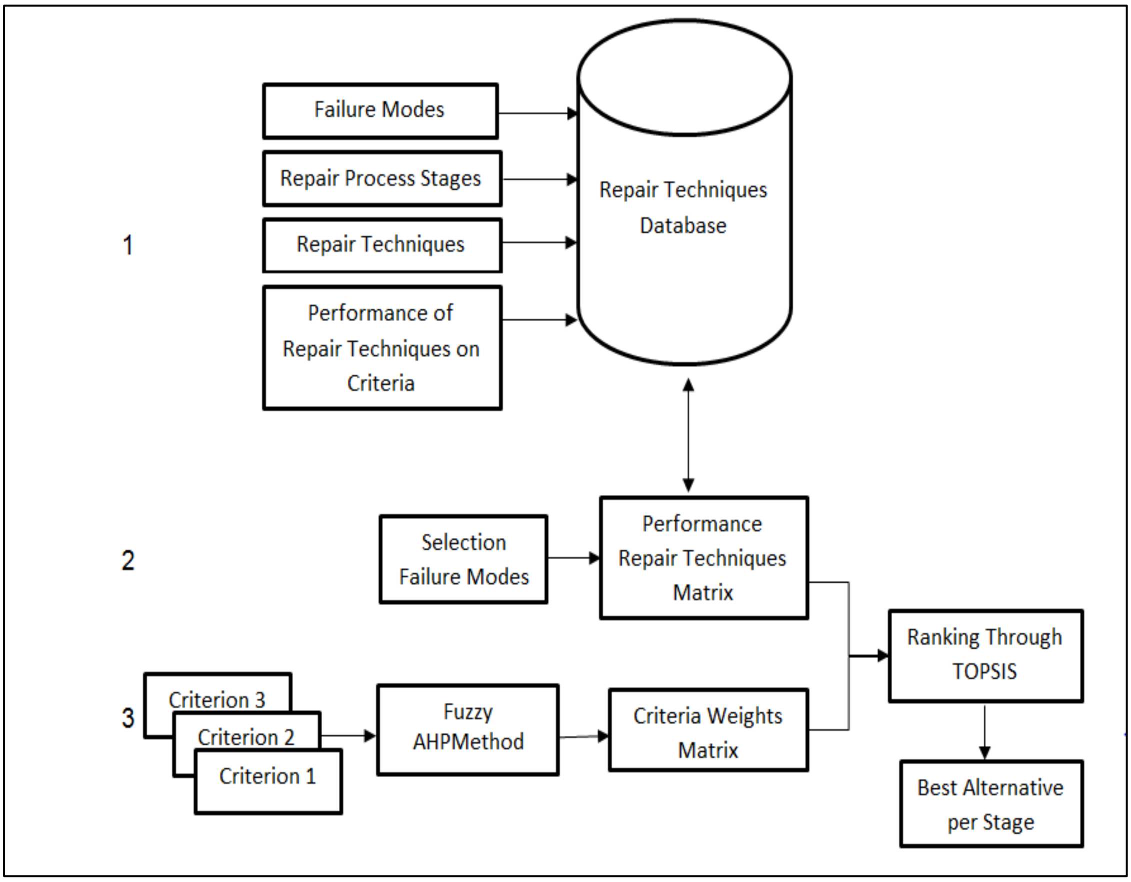


Figure 5-1 Decision Making Framework

In this framework there can be seen three important input moments, listed in Figure 5-1 through the numbers. The first one is the creation of a database of repair techniques, the second one is the selection of a particular failure mode and the last one is the criteria evaluation.

In the first input moment, the inputs are the performance on the evaluation criteria of the alternatives (or repair techniques) that may be given by industry or by experts.

The second input moment is the selection of the failure modes that affect the particular component. The selection of the failure modes affects the value of the performance of the repair techniques, as some repair techniques may be more adequate to some kind of failure mode than others. Through the failure mode selection data and the database of repair techniques a performance matrix is created.

The last input moment is the user evaluation of criteria. This stage is important as from the evaluation the weights of the criteria, representing the level of importance according to the user, are created. The weights are obtained through a Fuzzy AHP method. Once obtained the weight matrix and connected its values with the performance matrix, through the TOPSIS method the alternatives are ranked, suggesting so the best alternatives. The next paragraphs will explain in detail the algorithm process through the criteria selection, the fuzzy AHP weights and the TOPSIS ranking.

5.3 SELECTION OF CRITERIA

Critical in the algorithm functionality are the criteria, these are fundamental for two reasons. First reason is that they are at the basis of the weights obtained through the Fuzzy AHP system, the second reason is that the performance of the repair techniques are also evaluated in comparison to the criteria. The decision, of what criteria and related subcriteria to use in the paper, has been taken after analysing the existing literature. However the studies of 2 previous related research works used similar criteria, so for consistency reasons the criteria were selected in accordance to them. These criteria have been then validated by an expert working on a project with Rolls-Royce.

The three main criteria, after the analysis of the literature that has been selected in this paper, are cost, time, and quality. Those are indeed the typical trade-off criteria explained usually through the Iron Triangle (Atkinson, 1999).

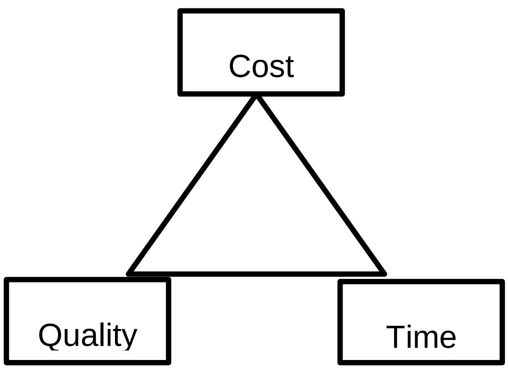


Figure 5-2 Iron Triangle (Atkinson, 1999)

This criteria can however be divided in other sub-criteria that may help in a better understanding on how to evaluate the criteria themselves. However they will not be used in the Fuzzy AHP, in order to make the tool more user friendly and in order to reduce its complexity.

In particular the decision not to put the subcriteria has been taken because it will have made the third step of the framework (see previous chapter) more complex with the need of an evaluation, done by the user, for each of the subcriteria. The following table shows the sub-criteria that may help in the evaluation process. The subcriteria have been identified after a process of analysis of the literature (however brainstorming can also be used) after reading about key characteristics in repair techniques.

Table 5-1 Subcriteria

QUALITY	TIME	COST
Performance of repaired component	Time to repair	Operation Cost
Mean time before next breakdown	Set-up time repair technique	Cost of Labour
Reliability of repair		Cost of Material
Quality of the repair itself		Cost of Technology

5.4 FUZZY AHP

In order to produce the weights necessary to give different importance to the criteria a Fuzzy AHP is used.

The fuzzy AHP technique is based on a standard AHP technique but instead of having certain numbers it has fuzzy number in order to express the variability of people thoughts.

In this paper triangular fuzzy number are used because their large use in the literature and because introducing other examples like trapezoidal would have increased the complexity of the algorithm and increased the number of calculations for the software. As described in literature these fuzzy number are represented by 3 points:

$$A = (a_1, a_2, a_3) \tag{5-1}$$

The choice system that has been applied for the evaluation of the criteria is a 5 mark system. This has been selected based on the commonly used Likert scale. The strength of this system is that there is the possibility for the user to select a value that is intermediate, so not necessary positive or negative.

The TFN membership of a linguistic judgement for criteria can be represented like this way, as shown in the picture, for a 5 choices system (Wang, 2013)

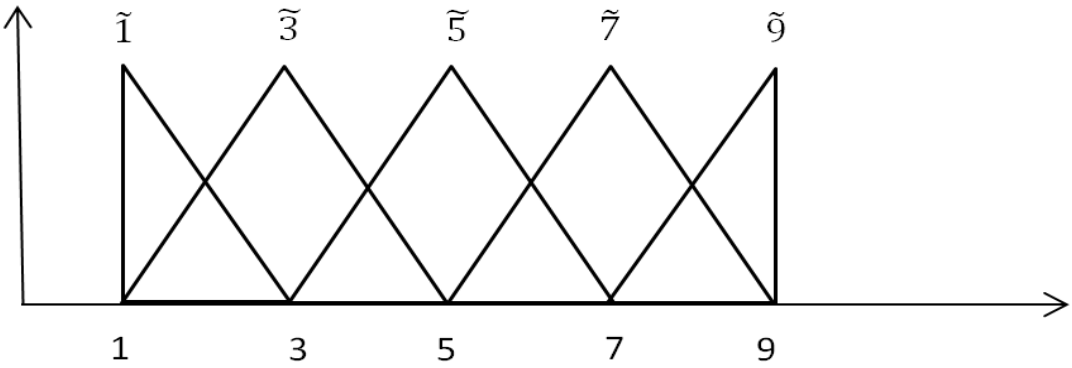


Figure 5-3 TFN membership of a linguistic judgement for criteria (Wang, 2013).

5.5 LINGUISTIC SCALE AND FUZZY NUMBER

As described before the evaluation of each criterion is made with linguistic scale of 5 values that are linked to triangular fuzzy numbers, a similar division to the one applied here can also be found in previous related papers (Wang, 2013).

In Table 5-2 for each Linguistic value or mark it is possible to see the related triangular fuzzy numbers.

Table 5-2 Linguistic scale for criterion of the user

Linguistic Scale	Related fuzzy numbers		
Not Important	1	1	3
Not Really Important	1	3	5
Important	3	5	7
Very Important	5	7	9
Extremely Important	7	9	9

5.6 CREATION OF THE WEIGHTS THROUGH THE FUZZY ALGORITHM

In this paragraph it is listed the steps necessary to develop the weights.

1. Construction of pairwise comparison matrices between all the criteria using the evaluations of the criteria with the linguistic judgments given by the user:

$$\tilde{A} = \begin{pmatrix} \tilde{a}_{11} & \cdots & \tilde{a}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \cdots & \tilde{a}_{nn} \end{pmatrix} \quad \textbf{(5-2)}$$

Where $\tilde{a}_{11}, \tilde{a}_{22}, \dots \tilde{a}_{nn}$ are all equal to 1, n is the number of criteria, and where $\tilde{a}_{ji} = 1/\tilde{a}_{ij}$ and $\tilde{a}_{ij} = (L_{\tilde{a}_{ij}} M_{\tilde{a}_{ij}},\ U_{\tilde{a}_{ij}})$ is a triangular fuzzy number

The values of $\tilde{a}_{ij}$ can be like this according to the value given by the user:

$$\tilde{a}_{ij} = \begin{cases} \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9} & \textit{if criteria i is more important than criteria j} \\ \tilde{1}^{-1}, \tilde{3}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1} & \textit{if criteria i is less important than criteria j} \end{cases} \quad \textbf{(5-3)}$$

2. The values of the fuzzy matrix created in step 1 are de-fuzzied, so the non-fuzzy value (a_{ij}) is obtained:

$$a_{ij} = \frac{\left(U_{\tilde{a}_{ij}} - L_{\tilde{a}_{ij}}\right) + \left(M_{\tilde{a}_{ij}} - L_{\tilde{a}_{ij}}\right)}{3} + L_{\tilde{a}_{ij}}$$

(5-4)

Where $L_{\tilde{a}_{ij}}$, $M_{\tilde{a}_{ij}}$ and $U_{\tilde{a}_{ij}}$ stand for the lower, middle and upper values of the fuzzy values of the matrix ($\tilde{a}_{ij}$).

3. Creation of the geometric mean ($\boldsymbol{m_i}$) and the weights ($\boldsymbol{w_i}$) for each criterion i through the eigenvector method. This is obtained through the use of the matrix created in the previous step. The formulas are:

$$m_i = (a_{i1} \otimes a_{i2} \otimes \ldots \otimes a_{in})^{1/n}$$ **(5-5)**

$$w_i = \widetilde{m}_i \otimes (\tilde{m}_1 \otimes \tilde{m}_2 \otimes \ldots \otimes \tilde{m}_n)^{-1}$$ **(5-6)**

At the end of this process the weights for the criteria are obtained that can be used for the subsequent ranking process.

5.7 EXPERT EVALUATION OF THE PERFORMANCE

For each repair techniques it has been associated a performance on criterion value between 1 and 9.

With 1 meaning very low performance and 9 meaning that the performance is very high.

All the values in the middle of this scale are gradations of performance, with the number 5 as discriminant between good and bad performance.

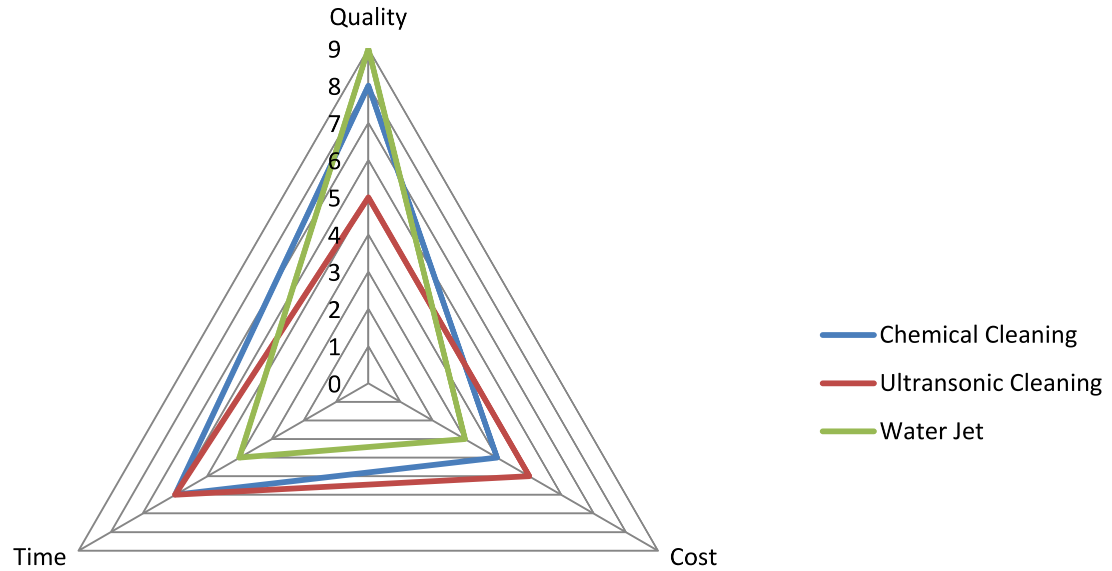
In the following page, a sheet, with the evaluation criteria and the alternatives, which experts can fill in, can be found.

COMPONENT: NGV DAMAGE MODE: ______________________________

S.NO	ACTIVITY	PROCESS	QUALITY	COST	TIME
	Notes				

Regarding the performance of time (or cost), number 9 means that the time is really short (or the cost is low) while 1 that the repairing time is long (or expensive). On the contrary for quality 9 means good level of quality and 1 means low level of quality.

The evaluation of the performance on criterion can graphically be seen in this way (in Figure 5-4 with the example of cleaning stage and as failure mode hot corrosion):



TOOLS		Stage		Quality	Cost	Time
Chemical Cleaning	1	Cleaning		8	4	6
Ultransonic Cleaning	2	Cleaning		5	5	6
Water Jet	3	Cleaning		9	3	4

Figure 5-4 Technique performance on criterion for cleaning stage for Hot Corrosion

5.8 CREATION OF THE RANK THROUGH TOPSIS METHOD

After obtained the weights the next step is to produce the rankings

1) the TOPSIS technique uses the weights obtained by the fuzzy AHP system and the performance of each alternative for failure mode from the repair technique database and the first step is to create a weighted performance matrix where in each position aw_{ij} we have:

$$aw_{ij} = w_j \times p_{ij} \quad \textbf{(5-7)}$$

Where w_j is the weight of the criteria *j* and p_{ij} is the performance of the alternative *i* in the criteria *j*.

2) The next step of the TOPSIS technique is to calculate for each alternative the shortest Euclidean distance from the best solution and the farthest Euclidean distance from the worst solution.

$$S_i^+ = \left[\sum \left(aw_{ij} - a_j^+\right)^2\right]^{1/2} \quad \textbf{(5-8)}$$

$$S_i^- = \left[\sum \left(aw_{ij} - a_j^-\right)^2\right]^{1/2} \quad \textbf{(5-9)}$$

With a_j^+ the highest value between the performance in the criteria j of the alternative, and a_j^- the lowest value between the performance in the criteria j of the alternative

The alternative with lowest similarity index to the worse is chosen as best and ranked first. The index formula is the following:

$$S_i^+/(S_i^+ + S_i^-) \quad \textbf{(5-10)}$$

6 SOFTWARE IMPLEMENTATION

The final decision was to implement the tool in a one software environment that is a tool that runs in just one programme. The software programme that was chosen, was Microsoft ® Excel , through the use of the application Visual Basic or VBA. The MCDM framework, described in a previous paragraph, was adapted to the software.

6.1 FRAMEWORK SOFTWARE TOOL AND DETAILS OF THE SOFTWARE

The framework of the software, can be represented in this way:

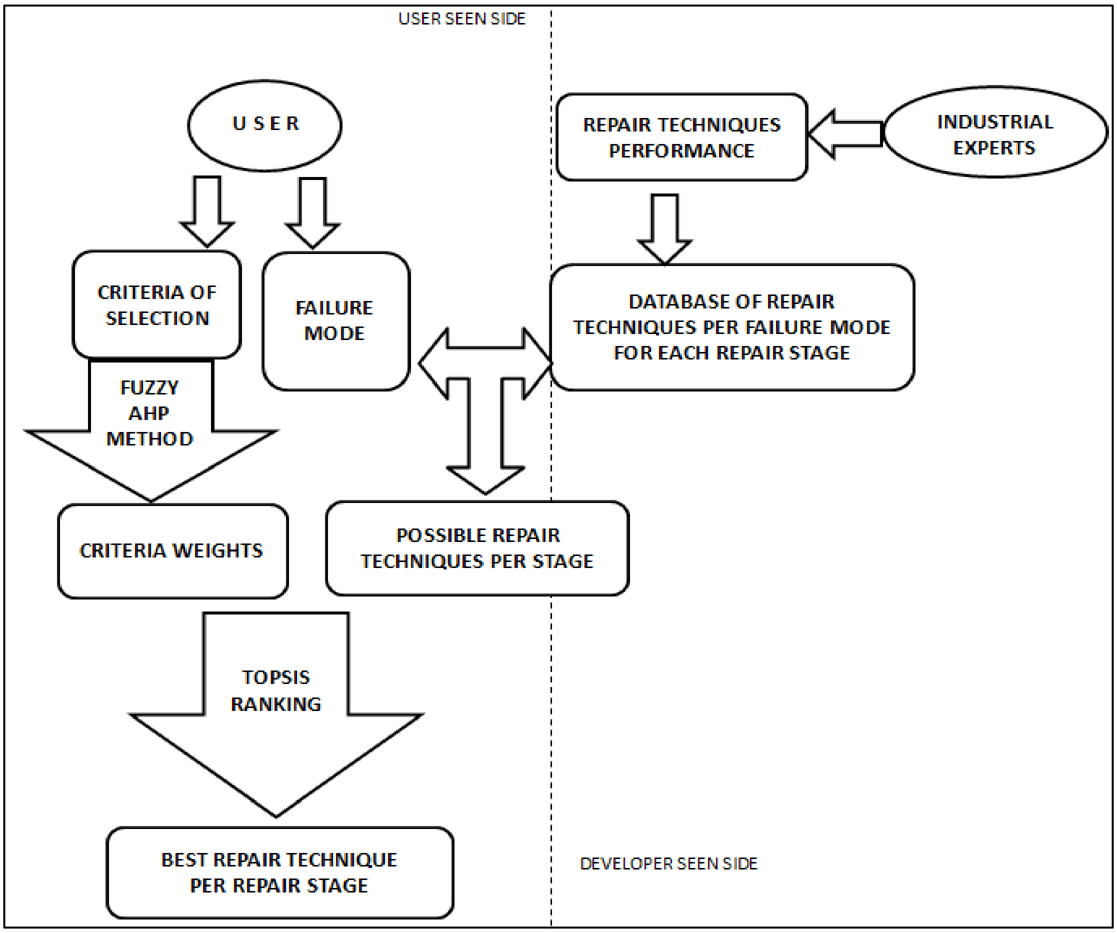


Figure 6-1 Software Framework

In the framework, shown in the previous picture, it is possible to see 2 sections: the User section and the Developer section.

The User section is relative to the part that the user can see of the software and modify, therefore it has to been user friendly. This part is the first sheets of the programme (Figure 6-2)

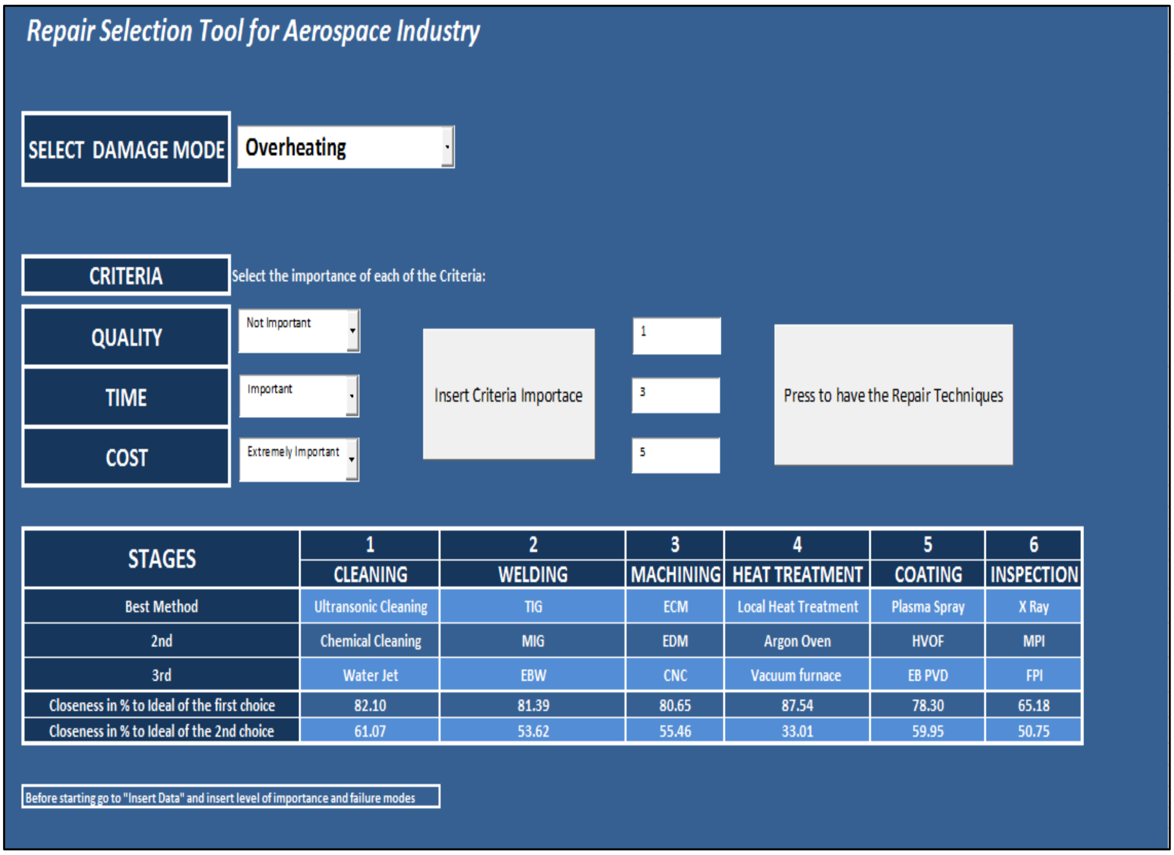


Figure 6-2 User page

In the User Side, the users can interact changing the values of the criteria (Quality, Time and Cost) and select the damage or failure modes they are interested in. The evaluation of the criteria (bespoken by the user) creates, through the fuzzy AHP logic, the weights necessary for the ranking and for giving the importance level for each of the criteria.

The Developer section needs to be completed with values and performances, before the user can start using the software. The Developer side, in particular, comprehend the algorithm, the database of repair techniques and performance. It is mandatory that this part if filled in and modified only by experts). Indeed in this stage the experts give an evaluation on the performance on the criteria (choosing a number between 1 and 9, where 1 is very low performance and 9 is very high performance) of each repair technique alternative for each step of the repair process. The software has a system which permits the auto-validation of itself through the evaluation of 5 experts. The average value of the 5 opinions will be the performance score for that technique for those criteria. Once all the opinions are taken these will be part of a database of repair techniques that can be seen in Figure 6-3.

TOOL PAPER VALIDATOR

TOOLS		Stage	Hot Corrosion			Creep Deflection			Thermal Fatigue			Overheating			Coating Distress			Distortion			Engine Object Damage		
			Quality	Cost	Time	Quality	Cost	Time	Quality	Cost	Time	Quality	Cost	Time	Quality	Cost	Time	Quality	Cost	Time	Quality	Cost	Time
Chemical Cleaning	1	Cleaning	8	4	6	7	6	8	9	2	6	9	2	9	6	7	5	8	3	8	6	8	9
Ultrasonic Cleaning	2	Cleaning	5	5	6	4	7	8	7	3	6	6	3	9	3	8	5	5	4	8	3	9	9
Water Jet	3	Cleaning	9	3	4	8	5	6	9	1	4	9	1	7	7	6	3	9	2	6	7	7	7
MIG	4	Welding	7	6	3	6	8	5	9	4	3	8	4	6	5	9	2	7	5	5	5	9	6
TIG	5	Welding	6	8	4	5	9	6	8	6	4	7	6	7	4	9	3	6	7	6	4	9	7
EBW	6	Welding	9	3	6	8	5	8	9	1	6	9	1	9	7	6	5	9	2	8	7	7	9
CNC	7	Machining	6	4	5	5	6	7	8	2	5	7	2	8	4	7	4	6	3	7	4	8	8
EDM	8	Machining	9	5	6	8	7	8	9	3	6	9	3	9	7	8	5	9	4	8	7	9	9
ECM	9	Machining	5	6	7	4	8	9	7	4	7	6	4	9	3	9	6	5	5	9	3	9	9
Vacuum furnace	10	Heat Treatment	7	4	4	6	6	6	9	2	4	8	2	7	5	7	3	7	3	6	5	8	7
Argon Oven	11	Heat Treatment	5	5	6	4	7	8	7	3	6	6	3	9	3	8	5	5	4	8	3	9	9
Local Heat Treatment	12	Heat Treatment	6	8	5	5	9	7	8	6	5	7	6	8	4	9	4	6	7	7	4	9	8
EB PVD	13	Coating	8	3	3	7	5	5	9	1	3	9	1	6	6	6	2	8	2	5	6	7	6
Plasma Spray	14	Coating	7	5	4	6	7	6	9	3	4	8	3	7	5	8	3	7	4	6	5	9	7
HVOF	15	Coating	8	4	5	7	6	7	9	2	5	9	2	8	6	7	4	8	3	7	6	8	8
X Ray	16	Inspection	9	5	3	8	7	5	9	3	3	9	3	6	7	8	2	9	4	5	7	9	6
MPI	17	Inspection	7	4	4	6	6	6	9	2	4	8	2	7	5	7	3	7	3	6	5	8	7
FPI	18	Inspection	5	3	5	4	5	7	7	1	5	6	1	8	3	6	4	5	2	7	3	7	8

Tool names (possible to modify)

TOOLS	Stage
Chemical Cleaning	Cleaning
Ultrasonic Cleaning	Cleaning
Water Jet	Cleaning
MIG	Welding
TIG	Welding
EBW	Welding
CNC	Machining
EDM	Machining
ECM	Machinong
Vacuum furnace	Heat Treatment
Argon Oven	Heat Treatment
Local Heat Treatmen	Heat Treatment
EB PVD	Coating
Plasma Spray	Coating
HVOF	Coating
X Ray	Inspection
MPI	Inspection
FPI	Inspection

Figure 6-3 Repair techniques with performance per failure modes database

Through the selection of the desired failure mode, the user reduces the database to a part of it (just the one regarding that particular failure mode).

The expected ranking is elaborated through the TOPSIS method (as shown in a previous paragraph) through the weights and the performance of the alternatives.

The software will then show in the first sheet the suggested 3 ranked techniques, and for the first 2 it will show the closeness to the ideal technique represented as percentage of closeness to the ideal solution. This last information may help in understanding how better the best solution is compared with the second ranked.

Finally one last important characteristics of the tool is that it is easily customisable . That means that all the techniques can be updated with new performance values, or be substituted with new better performing alternatives. Moreover also the failure modes and repair stages can be changed or modified. This makes the application of this tool possible in more fields and updatable if the parameters will change in the future.

In the following paragraphs there is a short description of the sheets of the tool.

6.1.1 SHEET 1 OR USER INSERT DATA SHEET

Figure 6-4 User Insert Data Sheet

This is the first sheet of the programme and here the user is requested to insert and add the inputs to the system (or to the second page). In order to insert the inputs it is necessary to press these 2 buttons. This step is necessary in order to start the system, and has to be done every time the software starts. This part is also customisable as the damage modes and the levels of importance can be modified (it is possible to change names), new ones can be added and the current ones can also be removed.

6.1.2 SHEET 2 or USER/OPERATOR'S INTERFACE

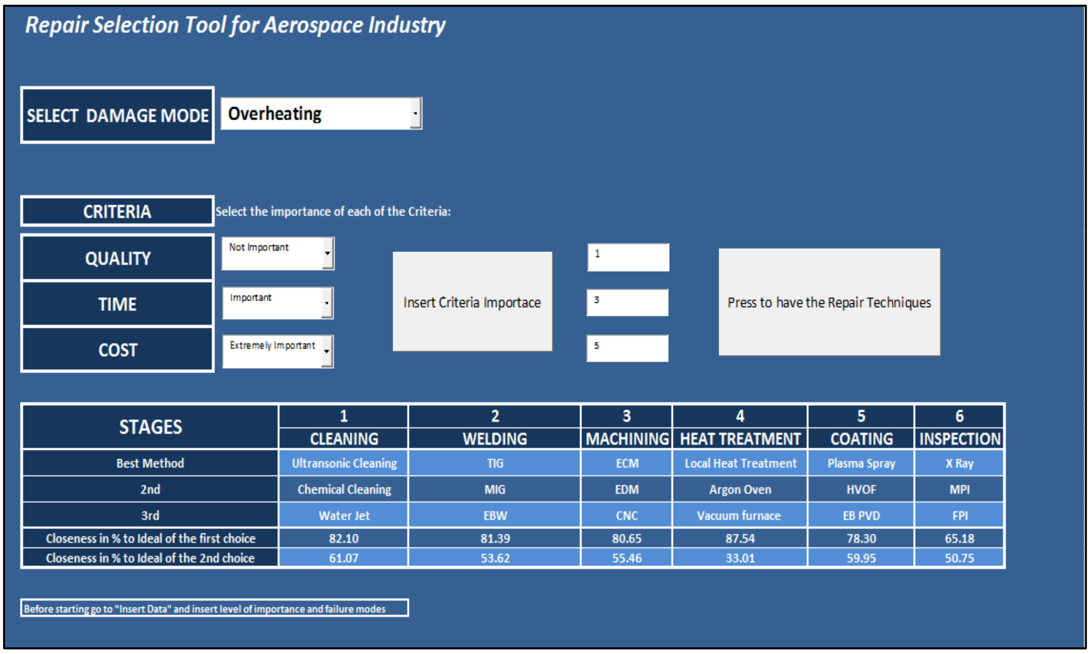


Figure 6-5 Operator Interface

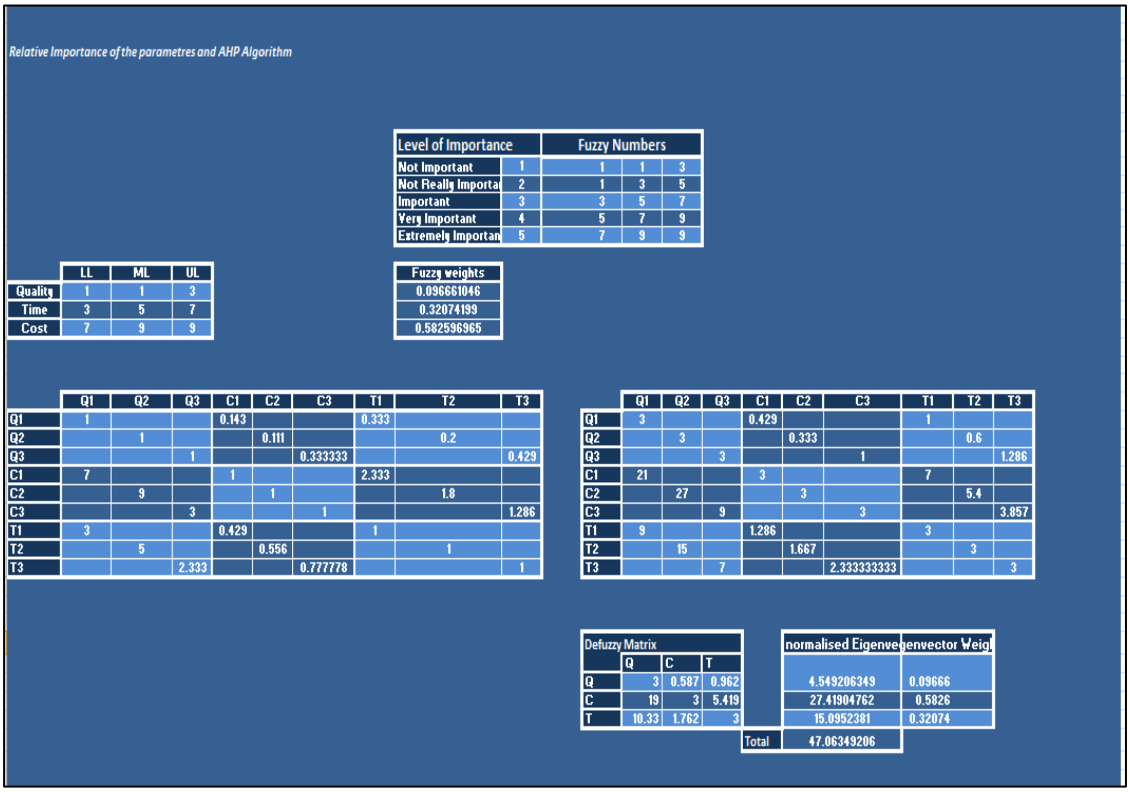
In sheet two, the user can select the damage mode, and give his preference on the criteria. Before doing so it is necessary to go to sheet 1 (see previous chapter). According to the preference given the tool will create importance level for each of the criteria.

Once selected the importance level the user has to press "The Insert Criteria Importance" button. This button will insert the data in the software and clear the field with the repair techniques. It is necessary to press also the "Press to have repair" technique button in order to have the results.

Once pressed the 2 buttons the software will generate the ranking for the 3 repair techniques and for the closeness to the ideal solution for the first 2.

6.1.3 DEVELOPER SIDE

6.1.3.1 SHEET 3 OR AHP ALGORITHM



Relative Importance of the parametres and AHP Algorithm

Level of Importance		Fuzzy Numbers		
Not Important	1	1	1	3
Not Really Importa	2	1	3	5
Important	3	3	5	7
Very Important	4	5	7	9
Extremely Importan	5	7	9	9

	LL	ML	UL
Quality	1	1	3
Time	3	5	7
Cost	7	9	9

Fuzzy weights
0.096661046
0.32074199
0.582596965

	Q1	Q2	Q3	C1	C2	C3	T1	T2	T3
Q1	1			0.143			0.333		
Q2		1			0.111			0.2	
Q3			1			0.333333			0.429
C1	7			1			2.333		
C2		9			1			1.8	
C3			3			1			1.286
T1	3			0.429			1		
T2		5			0.556			1	
T3			2.333			0.777778			1

	Q1	Q2	Q3	C1	C2	C3	T1	T2	T3
Q1	3			0.429			1		
Q2		3			0.333			0.6	
Q3			3			1			1.286
C1	21			3			7		
C2		27			3			5.4	
C3			9			3			3.857
T1	9			1.286			3		
T2		15			1.667			3	
T3			7			2.333333333			3

Defuzzy Matrix			
	Q	C	T
Q	3	0.587	0.962
C	19	3	5.419
T	10.33	1.762	3

	normalised Eigenve	genvector Weigl
	4.549206349	0.09666
	27.41904762	0.5826
	15.0952381	0.32074
Total	47.06349206	

Figure 6-6 AHP Algorithm

In this sheet it is possible to see how the algorithm works with the fuzzy matrices, the defuzzied matrix and the eigenvector. This sheet can be modified just by the developers and by experts of AHP, repair tool experts and users are unable to access the page.

6.1.3.2 SHEET 4-10 FAILURE MODES SHEET AND TOPSIS ALGORITHM TO RANK

Thermal Fatigue																
							WEIGHTED MATRIX									
Cleaning																
		Quality	Cost	Time	Final Value		Quality	Cost	Time	Dis wor:	Dis best	Max Qu:	Max Co:	Max Time	Siw	Closiness To Ideal Solution
	Chemical Cleaning	9	2	6	3,9596	2	0,8699	1,1652	1,9245	0,8879	0,5826	0,8699	1,7478	1,9245	0,3962	60,38
	Ultransonic Cleaning	7	3	6	4,3489	1	0,6766	1,7478	1,9245	1,3301	0,1933	Min Qua	Min Cos	Min Time	0,1269	87,31
	Water Jet	9	1	4	2,7355	3	0,8699	0,5826	1,283	0,1933	1,3301	0,6766	0,5826	1,283	0,8731	12,69
Welding																
		Quality	Cost	Time	Final Value		Quality	Cost	Time	Dis wor:	Dis best	Max Qu:	Max Co:	Max Time	Siw	Closiness To Ideal Solution
	MIG	9	4	3	4,1626	2	0,8699	2,3304	0,9622	1,7505	1,5111	0,8699	3,4956	1,9245	0,4633	53,669
	TIG	8	6	4	5,5518	1	0,7733	3,4956	1,283	2,9306	0,6487	Min Qua	Min Cos	Min Time	0,1812	81,876
	EBW	9	1	6	3,377	3	0,8699	0,5826	1,9245	0,9671	2,913	0,7733	0,5826	0,9622	0,7508	24,924
Machining																
		Quality	Cost	Time	Final Value		Quality	Cost	Time	Dis wor:	Dis best	Max Qu:	Max Co:	Max Time	Siw	Closiness To Ideal Solution
	CNC	8	2	5	3,5422	3	0,7733	1,1652	1,6037	0,0967	1,3336	0,8699	2,3304	2,2452	0,9324	6,7582
	EDM	9	3	6	4,5422	2	0,8699	1,7478	1,9245	0,6926	0,6651	Min Qua	Min Cos	Min Time	0,4899	51,014
	ECM	7	4	7	5,2522	1	0,6766	2,3304	2,2452	1,3301	0,1933	0,6766	1,1652	1,6037	0,1269	87,31
Heat Treatment																
		Quality	Cost	Time	Final Value		Quality	Cost	Time	Dis wor:	Dis best	Max Qu:	Max Co:	Max Time	Siw	Closiness To Ideal Solution
	Vacuum furnace	9	2	4	3,3181	3	0,8699	1,1652	1,283	0,1933	2,4171	0,8699	3,4956	1,9245	0,9259	7,4059
	Argon Oven	7	3	6	4,3489	2	0,6766	1,7478	1,9245	0,8666	1,7585	Min Qua	Min Cos	Min Time	0,6699	33,012
	Local Heat Treatment	8	6	5	5,8726	1	0,7733	3,4956	1,6037	2,3543	0,335	0,6766	1,1652	1,283	0,1246	87,544

Figure 6-7 TOPSIS Raking and failure modes

There is a sheet for each failure mode and in these sheets there are calculations to arrive to the final rankings through TOPSIS' similarity index for each stage of the repair process.

The particularity is that if in the last sheet Tool Paper and validator the names of the repair techniques are changed, all these sheets modify also the names of the techniques.

These sheets cannot be modified by users and technique experts but only by developers.

6.1.3.3 SHEET TOOL PAPER AN VALIDATOR

Hot Corrosion

TOOLS		Expert 1			Expert 2			Expert 3			Expert 4			Expert 5			Mean		
		Quality	Cost	Time	Quality	Cost	Time	Quality	Cost	Time	Quality	Cost	Time	Quality	Cost	Time	Quality	Cost	Time
Chemical Cleaning	1	8	4	6	8	4	6	8	4	6	8	4	6	8	4	6	8	4	6
Ultransonic Cleaning	2	5	5	6	5	5	6	5	5	6	5	5	6	5	5	6	5	5	6
Water Jet	3	9	3	4	9	3	4	9	3	4	9	3	4	9	3	4	9	3	4
MIG	4	7	6	3	7	6	3	7	6	3	7	6	3	7	6	3	7	6	3
TIG	5	6	8	4	6	8	4	6	8	4	6	8	4	6	8	4	6	8	4
EBW	6	9	3	6	9	3	6	9	3	6	9	3	6	9	3	6	9	3	6
CNC	7	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5
EDM	8	9	5	6	9	5	6	9	5	6	9	5	6	9	5	6	9	5	6
ECM	9	5	6	7	5	6	7	5	6	7	5	6	7	5	6	7	5	6	7
Vacuum furnace	10	7	4	4	7	4	4	7	4	4	7	4	4	7	4	4	7	4	4
Argon Oven	11	5	5	6	5	5	6	5	5	6	5	5	6	5	5	6	5	5	6
Local Heat Treatment	12	6	8	5	6	8	5	6	8	5	6	8	5	6	8	5	6	8	5
EB PVD	13	8	3	3	8	3	3	8	3	3	8	3	3	8	3	3	8	3	3
Plasma Spray	14	7	5	4	7	5	4	7	5	4	7	5	4	7	5	4	7	5	4
HVOF	15	8	4	5	8	4	5	8	4	5	8	4	5	8	4	5	8	4	5
X Ray	16	9	5	3	9	5	3	9	5	3	9	5	3	9	5	3	9	5	3
MPI	17	7	4	4	7	4	4	7	4	4	7	4	4	7	4	4	7	4	4
FPI	18	5	3	5	5	3	5	5	3	5	5	3	5	5	3	5	5	3	5

Figure 6-8 Expert database

This sheet is the central part of the developer side. Here 5 experts or less can evaluate and give a rating (1 to 9, with 9 extremely good) to the performance on criteria for the repair techniques. The average between the 5 evaluations is used as rating for the repair technique. This process is done for all failure modes. The 5 evaluations are used as autovalidation of the tool itself. Indeed the an error in evaluating a technique made by one expert is corrected by the evaluations of the remainder experts.

In the top of the same sheet there is also the performance of the techniques for each failure modes with the average values. These values are used in the TOPSIS calculations for the final rankings in the sheets 4 to 10. On the right there is a list where it is possible to change the name of the techniques (a change here will modify the names throughout all the software).

TOOL PAPER VALIDATOR

TOOLS		Stage	Hot Corrosion			Creep Deflection			Thermal Fatigue			Overheating			Coating Distress			Distortion			Engine Object Damage		
			Quality	Cost	Time	Quality	Cost	Time	Quality	Cost	Time	Quality	Cost	Time	Quality	Cost	Time	Quality	Cost	Time	Quality	Cost	Time
Chemical Cleaning	1	Cleaning	8	4	6	7	6	8	9	2	6	9	2	9	6	7	5	8	3	8	6	8	9
Ultransonic Cleaning	2	Cleaning	5	5	6	4	7	8	7	3	6	6	3	9	3	8	5	5	4	8	3	9	9
Water Jet	3	Cleaning	9	3	4	8	5	6	9	1	4	9	1	7	7	6	3	9	2	6	7	7	7
MIG	4	Welding	7	6	3	6	8	5	9	4	3	8	4	6	5	9	2	7	5	5	5	9	6
TIG	5	Welding	6	8	4	5	9	6	8	6	4	7	6	7	4	9	3	6	7	6	4	9	7
EBW	6	Welding	9	3	6	8	5	8	9	1	6	9	1	9	7	6	5	9	2	8	7	7	9
CNC	7	Machining	6	4	5	5	6	7	8	2	5	7	2	8	4	7	4	6	3	7	4	8	8
EDM	8	Machining	9	5	6	8	7	8	9	3	6	9	3	9	7	8	5	9	4	8	7	9	9
ECM	9	Machining	5	6	7	4	8	9	7	4	7	6	4	9	3	9	6	5	5	9	3	9	9
Vacuum furnace	10	Heat Treatment	7	4	4	6	6	6	9	2	4	8	2	7	5	7	3	7	3	6	5	8	7
Argon Oven	11	Heat Treatment	5	5	6	4	7	8	7	3	6	6	3	9	3	8	5	5	4	8	3	9	9
Local Heat Treatment	12	Heat Treatment	6	8	5	5	9	7	8	6	5	7	6	8	4	9	4	6	7	7	4	9	8
EB PVD	13	Coating	8	3	3	7	5	5	9	1	3	9	1	6	6	6	2	8	2	5	6	7	6
Plasma Spray	14	Coating	7	5	4	6	7	6	9	3	4	8	3	7	5	8	3	7	4	6	5	9	7
HVOF	15	Coating	8	4	5	7	6	7	9	2	5	9	2	8	6	7	4	8	3	7	6	8	8
X Ray	16	Inspection	9	5	3	8	7	5	9	3	3	9	3	6	7	8	2	9	4	5	7	9	6
MPI	17	Inspection	7	4	4	6	6	6	9	2	4	8	2	7	5	7	3	7	3	6	5	8	7
FPI	18	Inspection	5	3	5	4	5	7	7	1	5	6	1	8	3	6	4	5	2	7	3	7	8

Tool names (possible to modify)

TOOLS	Stage
Chemical Cleaning	Cleaning
Ultransonic Cleaning	Cleaning
Water Jet	Cleaning
MIG	Welding
TIG	Welding
EBW	Welding
CNC	Machining
EDM	Machining
ECM	Machinong
Vacuum furnace	Heat Treatment
Argon Oven	Heat Treatment
Local Heat Treatmen	Heat Treatment
EB PVD	Coating
Plasma Spray	Coating
HVOF	Coating
X Ray	Inspection
MPI	Inspection
FPI	Inspection

Figure 6-9 Tool Paper Validator

7 THE SELECTED AERO COMPONENT

The next step of the thesis work has been the study of failure modes and repair techniques for an aero engine. Unfortunately the parts that can be damaged in an engine are several, so due to time and scope constraints it has been decided to focus just on nozzle guide vanes. The operations, which have been done with the nozzle guide vanes, can easily be replicated for other components of an engine. All the data collected are about the nozzle guide vanes.

The process applied to collect data started with an extensive analysis and research in the literature on the nozzle guide vanes, due the reasons specified before not all the engine. Once having a complete understanding of the component, a further analysis of literature was conducted in order to find out the failure modes and which are the repair techniques. The information collected from literature on failure and repair modes had however to be validated and in this paper it has been validated through suggestions and opinions of a direct connected to industry expert, with knowledge of methods used in industry and in particular in Rolls-Royce . Finally, the performances needed to be collected through opinions of experts or industry. The tool is created in a way that permits the evaluation of a pool of 5 experts (so the average is considered). Due to no direct contacts with industry experts, the values in the case study, showed in the final part of the results chapter, are collected through the opinion and suggestion of an expert working on a Rolls-Royce funded project related with this thesis work.

So the next paragraphs will have a short description of the data collected, in particular it will show how nozzle guide vanes work, failure modes and repair techniques and repair stages.

7.1.1 DESCRIPTION OF NOZZLE GUIDE VANES

In general in order to create a driving torque, the turbine consists of multiple stages of one row of moving blades and one row of stationary nozzle guide vanes (see Figure 7-1 and Figure 7-2 for position in an engine).

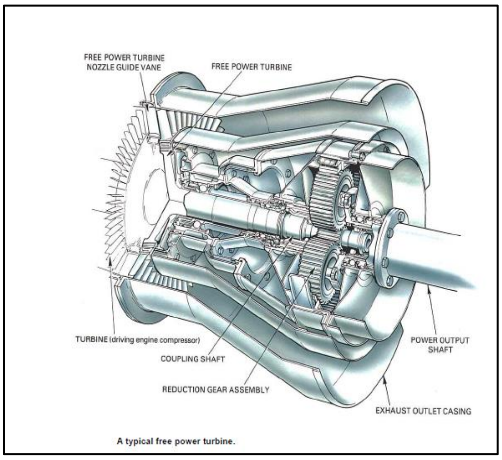


Figure 7-1 A typical free power turbine (Rolls Royce plc, 1996).

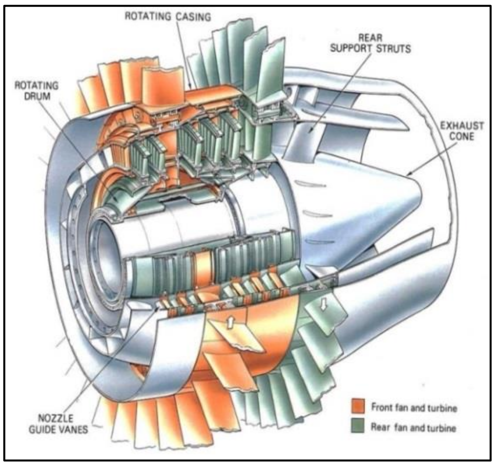


Figure 7-2 Nozzle guide vanes in a free power contra-rotating turbine (Rolls Royce plc, 1996)

So Nozzle Guide Vanes (also called NGV's) are static components that are commonly used in the turbine of a gas turbine engine, where they direct the flow of incoming exhaust gasses onto the rotating turbine blades (Rolls-Royce Plc, 1990) maximising the downstream blade performance. (Rolls-royce.com, 2014)

The structure Nozzle guide vanes is shown in the following picture (see Figure 7-3).

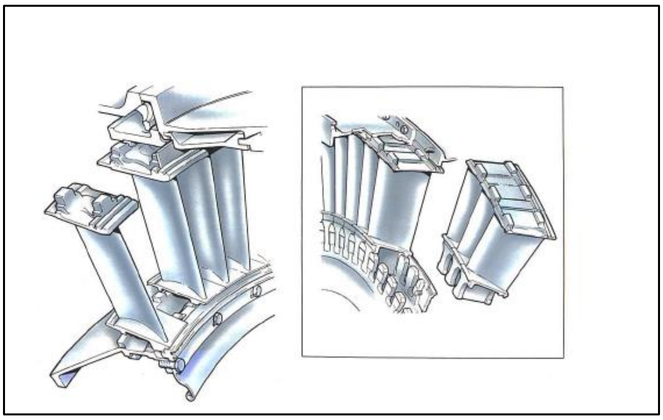


Figure 7-3 Details nozzle guide vanes (Rolls Royce plc, 1996).

Another characteristic is that the NGVs, differently than the turbine blades, are not subject the same rotational stresses because they are stationary. Therefore the property that is most required is heat resistance (Rolls Royce, 1996).

7.1.2 FAILURE MODES IN NOZZLE GUIDE VANES

In the following pictures it can be seen how a NGV that need repair (Figure 7-4) is and how it is after a repair process (Figure 7-5).

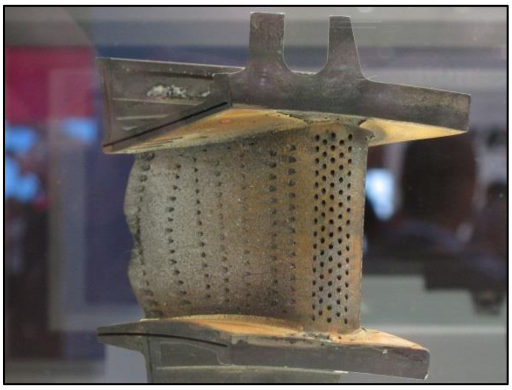


Figure 7-4 NGV before the repair process (Cleynen, 2013).

Figure 7-5 NGV after the repair process (Cleynen, 2013).

In order to study the failure modes several papers in literature were analysed (A V Roe Canada Ltd, 1953; Mack, Drtina and Lang, 1999; Air Canada 1974; Bewley, 2012; McAlpin et al., 2003; Pallos, 2001; Rolls Royce, 1996;Samuel, Mukhopadlhyay and Shankar, 2006; Meher-Homji and Gabriles, 1998; Blachnio and Pawlak, 2011; Johnson, 2006; U S. Naval Air Engineering Center, 1974).

And a short taxonomy collected from literature can be so listed (Table 7-1):

Table 7-1 Failure Modes

1	**HIGH TEMPERATURE OXIDATION**
2	**PLASTIC DEFORMATIONS**
3	**MATERIAL OVERHEATING**
4	**FATIGUE:** a) Thermal fatigue b) Low cycle fatigue c) High cycle fatigue
5	**CORROSIONS:** a) Hot corrosion b) Intercrystalline corrosion c) Chemical corrosion
6	**CRACKS:** a) Fatigue Cracks b) Monotonic Cracks
7	**CREEPING**
8	**MELTING** (caused by excessive long lasting contact with high temperature exhaust gasses)
9	**FOREIGN MATTER AFFECTING GUIDE VANES**
10	**SURFACE SCRATCHES**
11	**EROSIVE WEAR**
12	**FAILURE ATTRIBUTED TO EXCESSIVE VIBRATION**
13	**DETERIORATION OR THERMAL AGENING**

However in order to do less complex the visualisation for the software, and to reduce the number of choices for the users, the distinction made by Patnaik and Thamburaj(1999) has been used that can be seen in the following Table 7-2 where they are listed according to frequency of happening.

Table 7-2 NGVs common failure modes in Patnaik and Thamburaj 1999

Nozzle Guide vanes most common failure modes	
Primary	***Secondary***
Hot Corrosion	Distortion
Thermal Fatigue	Engine Object Damage
Coating Distress	
Overheating	
Creep Deflection	

7.1.3 REPAIR STAGES AND REPAIR TECHIQUES

Also for the repair stages the information from the literature has been used (Hastie, 2010; Pallos, 2001; Rolls Royce, 1996; Blachnio and Pawlak, 2011) and validated through the opinion of an expert working on a project with Rolls-Royce.

So in general from literature the repair stages for NGVs can be summarised like these:

Table 7-3 Repair Stages

1	Inspection
2	Cleaning
3	Welding
4	Machining
5	Heat Treatment
6	Coating
7	Inspection

The assumption made in the development of the tool however is that the process starts after the first inspection is already done, and that the decision of repairing the component is already taken. The final inspection will however use similar repair techniques as the first one so no information is lost making this assumption.

In order to have a complete understanding for each repair stage, several techniques were found in literature.

These can be summarised in these lists and tables:

Table 7-4 Cleaning techniques

Cleaning	Chemical Cleaning
	Ultrasonic Cleaning
	Waterjet
	Abrasive Blasting
	Manual Cleaning

Table 7-5 Welding techniques

Welding	Metal Inert Gas (MIG)
	Tugsten Inert Gas (TIG)
	Electron Beam Welding (EBW)
	Resistive spot welding (RSW)
	ElectroSlag Welding (ESW)
	Brazing

Table 7-6 Machining and finishing techniques

Machining and Finishing	Computer numerical control (CNC) machining
	Electrical discharge machining (EDM)
	Electrochemical Machining (ECM)
	Photochemical Machining (PCM)
	Ultrasonic Machining

Table 7-7 Heat Treatment techniques

Heat Treatment	Vacuum Furnace
	Argon Oven
	Local Heat Treatment

Table 7-8 Coating Techniques

Coating	Electron Beam Physical Vapour deposition (EB PVD)
	Air plasma spraying (APS)
	High Velocity oxy-fuel coating spray (HVOF)
	Electrostatic spray assisted vapour deposition (ESAVID)
	Direct Vapour Depsition

Table 7-9 Inspection Techniques

Inspection	Visual Inspection
	Magnetic particle inspection (MPI)
	Fluid Penetrant Inspection (FPI)
	Laser Techniques
	Acoustic emission inspection
	Radio Graphic Inspection
	Eddy Current Inspection

For each repair technique, in order to reduce the complexity of the model, only 3 elements for each phase were selected, these were selected through the suggestions of an expert and they are the most common techniques currently used.

Table 7-10 Selected Repair Techniques

REPAIR STAGES					
Cleaning	**Welding**	**Machining**	**Heat Treatment**	**Coating**	**Inspection**
Chemical Cleaning	MIG	CNC	Vacuum Furnace	EB PVD	X Ray
Ultrasonic Cleaning	TIG	EDM	Argon Oven	Plasma Spray	MPI
Water Jet	EBW	ECM	Local Heat Treatment	HVOF	FPI

8 CASE STUDY OF THE SELECTION OF REPAIR TECHNIQUES FOR THE NGVS

Two examples or case studies have been made in order to test the tool. Note well for the case studies, only the opinions and suggestions of one expert has been used. In both examples there hot corrosion has been considered as failure mode and as stage of the repair process the cleaning. The difference between the 2 examples is the evaluation of the criteria made by the user. This will however produce different results in the ranking and this will demonstrate the functionality, applicability of the tool.

In addition the performances are the same and the failure mode is the same for both examples and it will be Hot Corrosion.

Table 8-1 Performance of Alternatives for Cleaning

Repair Alternatives	Quality perf.	Cost perf.	Time perf.
Chemical Cleaning	8	4	6
Ultransonic Cleaning	5	5	6
Water Jet	9	3	4

8.1 EXAMPLE A

1. Criteria from user evaluation

Table 8-2 User evaluation example A

CRITERIA	**Criterion Importance**	**Related Fuzzy Numbers**
Quality	Extremely Important	7 9 9
Cost	Important	3 5 7
Time	Not Important	1 1 3

2. Fuzzy Matrix created for example A:

$$\begin{pmatrix} 1\ 1\ 1 & \frac{7}{3}\ \frac{9}{5}\ \frac{9}{7} & 7\ 9\ 3 \\ \frac{3}{7}\ \frac{5}{9}\ \frac{7}{9} & 1\ 1\ 1 & 3\ 5\ \frac{7}{3} \\ \frac{1}{7}\ \frac{1}{9}\ \frac{3}{9} & \frac{1}{3}\ \frac{1}{5}\ \frac{3}{7} & 1\ 1\ 1 \end{pmatrix}$$

3. Eigenvector Weights $\begin{pmatrix} Quality & 0{,}582597 \\ Cost & 0{,}320742 \\ Time & 0{,}096661 \end{pmatrix}$

4. Performance Matrix

Table 8-3 Performance Matrix

			Hot Corrosion		
Alternative Techniques		Stage	Quality	Cost	Time
Chemical Cleaning	1	Cleaning	8	4	6
Ultransonic Cleaning	2	Cleaning	5	5	6
Water Jet	3	Cleaning	9	3	4

5. Weighted performance Matrix for TOPSIS

Table 8-4 Weighted Matrix example A

Alternatives	Quality	Cost	Time
Chemical Cleaning	4,660776	1,282968	0,579966
Ultransonic Cleaning	2,912985	1,60371	0,579966
Water Jet	5,243373	0,962226	0,386644

6. Values of positive ideal solution and negative ideal solution

Table 8-5 Positive and negative ideal example A

	Quality	Cost	Time
Positive Ideal Solution	5,243372681	1,60370995	0,57996627
Negative Ideal Solution	2,912984823	0,96222597	0,38664418

7. Final Ranking

Table 8-6 Final Ranking example A

Alternatives	Distance negative	Distance positive	Similarity to worse	% Closeness to ideal	RANK
Chemical Cleaning	1,7874624	0,665052364	0,271172	72,88284	2
Ultrasonic Cleaning	0,6699814	2,330387858	0,7767	22,32997	3
Water Jet	2,3303879	0,669981438	0,2233	77,67003	1

8.2 EXAMPLE B

1. Criteria from user evaluation

Table 8-7 User Evaluation example B

CRITERIA	Criterion Importance	Related Fuzzy Numbers
Quality	Not Important	1 1 3
Cost	Extremely Important	7 9 9
Time	Very Important	5 7 9

2. Fuzzy Matrix created for example B:

$$\begin{pmatrix} 1\,1\,1 & \frac{1}{7}\,\frac{1}{9}\,\frac{3}{9} & \frac{1}{5}\,\frac{1}{7}\,\frac{3}{9} \\ 7\,9\,3 & 1\,1\,1 & \frac{7}{5}\,\frac{9}{7}\,1 \\ 5\,7\,3 & \frac{5}{7}\,\frac{7}{9}\,1 & 1\,1\,1 \end{pmatrix}$$

3. Eigenvector Weights $\begin{pmatrix} Quality & 0{,}084523 \\ Cost & 0{,}509220 \\ Time & 0{,}406255 \end{pmatrix}$

4. Performance Matrix Hot Corrosion

Table 8-8 Performance Matrix

			Hot Corrosion		
Alternative Techniques		Stage	Quality	Cost	Time
Chemical Cleaning	1	Cleaning	8	4	6
Ultransonic Cleaning	2	Cleaning	5	5	6
Water Jet	3	Cleaning	9	3	4

5. Weighted performance Matrix for TOPSIS

Table 8-9 Weighted Matrix example B

Alternatives	Quality	Cost	Time
Chemical Cleaning	0,6762	2,0369	2,4375
Ultransonic Cleaning	0,4226	2,5461	2,4375
Water Jet	0,7607	1,5277	1,6250

6. Values of positive ideal solution and negative ideal solution

Table 8-10 Positive and negative ideal example B

	Quality	Cost	Time
Positive Ideal Solution	0,76071496	2,54610108	2,4375354
Negative Ideal Solution	0,422619422	1,52766065	1,6250236

7. Final Ranking

Table 8-11 Final Raking

Alternatives	Distance negative	Distance positive	Similarity to worse	% Closeness to ideal	RANK
Chemical Cleaning	0,9918565	0,51618748	0,342289	65,77106	2
Ultrasonic Cleaning	1,3028416	0,338095538	0,206038	79,39619	3
Water Jet	0,3380955	1,302841639	0,793962	20,60381	1

9 DISCUSSIONS

The aim of the thesis was developing an algorithm and a tool that made it possible to help future operators and users in the decision making when there are several parameters to consider. In order to do that the relevant literature review brought to the decision to use a combination of two methods. The first method is nothing else than a fuzzy AHP technique that has been used in the determination of the weights of the criteria. The decision to use this technique has been taken because all the massive research done on it, to demonstrate its functionality. The TOPSIS technique was added in the last part for ranking purpose because of the useful information that it gives in addition to normal weighted sum, moreover as is stated in the research review chapter several studies have showed that the results are in the end similar on a limited amount of data. Indeed from the similarity to the worst condition it can be created an index of closeness to the best positive solution (that is the reciprocal). The positive ideal solution is however a fictional alternative that takes in account the best performance of the alternatives for each criterion, but however it can be used as ideal solution. From the analysis of this distance it is indeed possible to understand if the techniques are close to each other or if a technique is superior to all the others.

However another interesting point of the tool is that it has got also the weighted sum inside as possible comparison with the TOPSIS technique. And it has been happening that when the weighted sum was ranking the alternatives in the same position (ie, two as second), the TOPSIS ranking was however classifying the alternatives in different position distinguishing between them, forcing each alternative to have a certain position in the rank. Moreover in general, unless the case described before, the weighted sum gave a ranking identical to the one of TOPSIS.

9.1 CONTRIBUTIONS

The main and principal contribution of this thesis research project is the creation of an evaluation algorithm and tool for repair technique selection. In order to produce this algorithm and tool, Fuzzy AHP and TOPSIS were selected based on extensive literature reviews.

Moreover the tool was developed in a one-software environment, which is Microsoft @ Excel through VBA, eliminating in this way problems of compatibility and complexity between software environments that has been found in previous research projects. A positive characteristic of this tool is that it can be easily modified and customised to the need of the users. In addition the case study on selection of repair techniques for Nozzle Guide Vanes, showed to an expert, demonstrated that the algorithm, the model and the tool are logic and applicable.

The data needed for the software on engine components were found in literature and validated by an expert. These data included the common failure and damage modes of the NGVs, as well as the frequently used repair stages and techniques. These data can be used as the basis of repair technique taxonomy for other future researches.

9.2 MAJOR LIMITATIONS

However, there have been some limitations emerged during this project. Indeed the project can be seen in 2 phases, where the first phase was the development of the MCDM tool, the second phase, was the research and the definition of the repair technologies. Regarding the first phase, the limitation in the development of the algorithm has been the lack of knowledge of other software than Excel VBA. If the developer had knowledge of other software probably the framework could have been developed in a different way or in a more user friendly version. Regarding the second phase, as there was no contact with industry the research has been done on the literature. The accuracy of the data and information collected is dependent to the experience of an expert working on a similar topic, who has connection to the industry and is currently working on a Rolls Royce funded research project. The lack of direct contact with industry has limited the possibilities to use the more detailed and precise repair techniques that are currently used in this field. So the literature has been the major source of this research, with a subsequent need of a validation process. However, if more information was provided by the industrial sector, the database in the software tool could be more detailed and precise. Another limitation has been the time at disposal for the thesis. The duration is a standard time, but it has limited to the scope of the project to just the development of a tool for a single component, nozzle guide vanes. If the time at disposal was greater several different components could have been analysed.

9.3 FUTURE WORK

To overcome the previous listed limitations, several possible activities and research works are suggested for future researches. First of all, it is necessary to highlight the need of direct and continuous interaction and exchange of information with industry, so it is possible to collect as much reliable information and data as possible for the enrichment and improvement of the decision making support tools database. Secondly the tool could be improved adding for each stage more repair techniques instead of the current 3 per stage (the decision of 3 most used tools has been taken in order to reduce the complexity of the algorithm). A possible future development of the software could even hold 5 repair techniques for each stage. Moreover a study on a hierarchical structure for the subcriteria, without making too complex for the user to select and give an evaluation of the criteria, may be done. Finally an interesting point could be developing criteria that do not use subjective evaluations but objective ones.

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10 CONCLUSIONS

After discovering the absence in literature of a tool and an algorithm that may help users in the selection of repair technique, the need for the development of a repair technology selection tool raised. The work done and the deliverables obtained during the thesis project can be described and synthesised in this bullet points:

1. A decision making framework was created, and the major tasks to be conducted in this project were defined;
2. A software tool was developed with Microsoft Excel® VBA. This tool has several functions, such as provide available alternative repair techniques for each stage of the repair process for certain products. And the recommended technique is based on the preference of the user. The tool is also completely customisable, with the possibility to add failure modes, change repair techniques, change the repair stages.
3. As analysing the entire engine was out of scope due to the limited duration of a thesis project, the analysis was done on a component. On the component analysed was then developed the case study: selection of repair technology. This gave also the possibility to validate the tool through industrial data.

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