Electronic identifier: 17963

Date of electronic submission: 22/03/2016

The University of Manchester makes unrestricted examined electronic theses and dissertations freely available for download and reading online via Manchester eScholar at http://www.manchester.ac.uk/escholar.

This print version of my thesis/dissertation is a TRUE and ACCURATE REPRESENTATION of the electronic version submitted to the University of Manchester's institutional repository, Manchester eScholar.
“Criticality Based

Strategic Decision Making Model

For

Maintenance & Asset Management”

A thesis submitted to the University of Manchester for the degree of

Doctor of Philosophy

In the Faculty of Engineering and Physical Sciences

2016

Mohammad Moghaddasazadeh Kermani

School of Mechanical, Aerospace and Civil Engineering
# Table of Contents

CHAPTER 1 – Introduction

1.1-Research Background ................................................................. 18  
1.2- Problem statement ...................................................................... 21  
1.3- Research Aims and Objective .................................................... 22  
1.4-Research Questions ....................................................................... 24  
1.5-Hypothesis .................................................................................... 24  
1.6-Limitations .................................................................................... 24  
1.7- Summary of research in 1st, 2nd and 3rd years ................................ 26  
1.8-Thesis Structure ............................................................................ 26  

CHAPTER 2 Literature review

2.1- Introduction ................................................................................. 29  
2.2-Reliability, Availability, Maintainability Concepts ............................... 30  
2.2.1-Introduction to RAM .................................................................. 30  
2.2.2- Reliability definition and Concept.............................................. 31  
2.2.3- Reliability Calculation ............................................................... 32  
2.2.4-Weibull Analysis ....................................................................... 33  
2.2.5- Availability ............................................................................... 36  
2.2.6-Maintainability ......................................................................... 38  
2.3-Current approach to learn from failures ........................................... 39  
2.3.1- Criticality Assessment Method .................................................. 39  
2.3.2-Failure Mode and Effective Criticality Analysis ............................... 40  
2.3.3-Fault Tree Analysis (FTA) .......................................................... 43  
2.3.4- Reliability Block Diagram ........................................................ 45  
2.3.5-System Types ........................................................................... 46  
2.4-Maintenance Strategy ...................................................................... 48  
2.4.1- Operate To Failure (OTF) .......................................................... 48
2.4.2- Fix Time Maintenance (FTM) ................................................................. 48
2.4.3- Skill Level Upgraded (SLU) ................................................................. 49
2.4.4- Condition Based Maintenance (CBM) .................................................... 49
2.4.5- Design Out Maintenance (DOM) ........................................................... 50
2.5- Decision Analysis .................................................................................... 50
2.6- Critical review of maintenance and asset management ............................ 52
  2.6.1- Identifying current gaps in the literature ............................................. 52
  2.6.2- Background of other literature review papers ..................................... 53
  2.6.3- Classification of published papers ....................................................... 54
  2.6.4- Critical commentary on published papers .......................................... 55
2.7- Conclusion ............................................................................................... 67

CHAPTER 3 Research methodology .................................................................. 68
  3.1- Introduction .......................................................................................... 68
  3.2- Approaches to research methodology in management sciences ............ 68
  3.3- A post positivist Epistemological foundation ........................................ 71
  3.4- Data Collection: Primary and Secondary data ....................................... 74
  3.5- Qualitative Exploration & Development of SDMM ............................... 76
  3.6- The Motive for Using Case Study Analysis ........................................... 78
  3.7- The Motive for Using Semi Structure Interview .................................... 79
  3.8- Development of SDMM using Fuzzy AHP approach .............................. 80
    3.8.1- Forming a decision making problem ................................................. 80
    3.8.2- MCDM and its usefulness ................................................................. 81
    3.8.3- Justification for using Fuzzy Logic ................................................... 82
    3.8.4- Justification for using AHP in present research ............................... 85
  3.9- Conclusion ............................................................................................ 90

CHAPTER 4: Case Study analysis ..................................................................... 91
  4.1- Introduction .......................................................................................... 91
4.2-The BP oilfield case study .......................................................................................... 92
  4.2.1-Introduction ........................................................................................................... 92
  4.2.2-Culture of asset management............................................................................... 93
  4.2.3- Criticality Assessment Method Used in the Plant .............................................. 94
  4.2.4-Maintenance strategy in the plant......................................................................... 96
  4.2.5-Critical commentary ............................................................................................ 97
  4.2.6-Developing a model for CBM implementation.................................................. 97
  2.4.7-Simulating BP oil process plant using Fuzzy AHP approach ......................... 106
  2.4.8-The contribution of fuzzy AHP approach to case study .................................... 112
4.3-Oil and gas production platform investigation ....................................................... 113
  4.3.1- Purpose of investigation ................................................................................... 113
  4.3.2- Criticality assessment practice for oil production platform ............................... 114
  4.3.3-Developing a maintenance scorecard ................................................................... 116
  4.3.4-Platform Vision ..................................................................................................... 116
  4.3.5-Three first level of maintenance objectives ....................................................... 116
  4.3.6-Three maintenance key performance indicators ................................................. 117
  4.3.7- Critical commentary .......................................................................................... 117
4.4- Shell case study ....................................................................................................... 117
  4.4.1-The purpose of case study ................................................................................... 117
  4.4.2-Selecting critical pumps in terms of production ............................................... 118
  4.4.3-Maintenance strategy implementation ............................................................... 118
  4.4.4- The Improvement of MTBF Results ................................................................. 119
  4.4.5-Critical Commentary .......................................................................................... 120
4.5-BP Texas City Disaster ............................................................................................ 120
  4.5.1- Background of disaster .................................................................................... 120
  4.5.2-incident and sequence of events ......................................................................... 121
  4.5.3-Failure model and effective analysis of the event .............................................. 124
4.5.4- Key organisational issues ................................................................. 125
4.5.5-Critical Commentary & SDMM ......................................................... 127
4.6-Conclusion ......................................................................................... 129

CHAPTER 5: Strategic Decision Making Model ......................................... 130

5.1-Introduction: .................................................................................... 130
5.2- SDMM and its development process ................................................. 133
  5.2.1- Critical thinking ........................................................................... 133
  5.2.2- Strategic concepts in maintenance management ......................... 135
  5.2.3- SDMM phase 1: The application of fuzzy logic ............................. 136
  5.2.4- SDMM phase 2: The application of AHP ..................................... 170
5.3- Approaches towards SDMM ............................................................... 173
5.4-SDMM implementation for BP Texas City refinery ............................ 174
5.5-SDMM Results ................................................................................... 188
  Scenario 1: BP cost-cutting policy ....................................................... 189
  Scenario 2: BP culture of safety as the first priority ............................. 192
5.6-Conclusion ......................................................................................... 194

CHAPTER 6: Discussion ........................................................................... 196

6.1-Introduction ....................................................................................... 196
6.2- Discussion of finding for hypothesis 1 .............................................. 197
  Limitation of decision analysis ............................................................ 197
  Evidence 1- Maintenance models are oversimplified ............................ 197
  Evidence 2: Data collection and analysis V.S Decision analysis .......... 200
  Evidence 3- CMMS Features as Function of Price ............................... 200
  Decision Support System (DSS) ............................................................. 201
  Operational Decision Support System (ODSS) .................................... 201
  ODSS vs SDSS ..................................................................................... 203
  Paper classification approach ............................................................... 205
7.3-Research Limitations ...................................................................................... 237
7.4-A guide for further research ....................................................................... 238
7.5-Industrial Proposal ....................................................................................... 240
    Data for technical perspective ..................................................................... 241
    Data for operational perspective ............................................................... 242
    Data for safety perspective ....................................................................... 242
    Data for financial perspective .................................................................. 243
7.6-Publications and academic attempts ............................................................. 246
References ........................................................................................................ 247
Appendix A ....................................................................................................... 257
    Discussion in COMADEM conference ..................................................... 257
Appendix B ....................................................................................................... 264
    Samples of Interviews transcripts with Industrial and academic experts ....... 264
        The first Interview with Mr. Tom Lenahan ........................................... 264
        The Second Interview with Mr. Tom Lenahan ..................................... 273
    Discussion with the academic professional ............................................. 278
        The first interview with Prof Ashraf Labib .......................................... 278
        The second interview with Prof Ashraf Labib .................................... 291
Appendix C ....................................................................................................... 298
    Sample of Covering letter for world Class companies ............................ 298
Appendix D ....................................................................................................... 299
    Sample of Email communications with World class companies ............... 299

Total Word Count: 70883
List of tables

Table 1-Cost versus safety matrix which indicates the rules in rule evaluation phase ........................................................................................................................................................................101
Table 2-Illustrates how the rules allocated for each cost and safety M.F ............. 102
Table 3-FMEA of the instrument contributed to BP Texas city disaster (CSB, 2007) ...........................................................................................................................................................................................................................................125
Table 4-The classification of equipment with respect to consequence of failure .... 139
Table 5-Classification of equipment with respect to likelihood of failure............. 140
Table 6-Rule generating process for equipment criticality w.r.t safety perspective 141
Table 7-The classification of equipment in terms of their pattern of failures........146
Table 8-Classification of equipment with respect to the reliability block diagram .146
Table 9-Rule generating process for equipment criticality w.r.t pattern of failure and RBD...........................................................................................................................................................................................................................................147
Table 10-The classification of equipment with respect to number of failure frequency ...........................................................................................................................................................................................................................................151
Table 11-The classification of equipment with respect to down time ................. 152
Table 12-Rule generating process for equipment criticality w.r.t down time and failure frequency ...........................................................................................................................................................................................................................................152
Table 13-Classification of equipment with respect to production loss [adopted from (Qi et al., 2015)] ...........................................................................................................................................................................................................................................156
Table 14-Classification of equipment with respect to maintenance cost ........... 156
Table 15-Rule generating process for equipment criticality w.r.t production loss and maintenance cost ...........................................................................................................................................................................................................................................157
Table 16-Category A: If All and/or at least 3 of out 4 MFs are (Very highly critical) V.H.C ...........................................................................................................................................................................................................................................163
Table 17-Category B: if at least 2 of out 4 MFs (Membership Functions) are H.C 164
Table 18-Category C: if at least 1 out of 4 M(Membership Functions) is Critical..165
Table 19-Category D:if at least 4 and/or 3 out of 4MF to be Medium critical then output MF is Critical ...........................................................................................................................................................................................................................................165
Table 20-Category E (Medium priority) if at least 2 out of 4MF are Medium critical output MF is Medium Critical...........................................................................................................................................................................................................................................166
Table 21-Category F (Low priority) :if at least 4 or 3 out of 4MF to be Low critical then output MF is Non or Low Critical...........................................................................................................................................................................................................................................167
Table 22-Rules that excluded from category F because of safety concern .......... 168
Table 23-If safety is low then the output M.F may varies between High and Medium .............................................................................................................. 168
Table 24--The typical table that need to be create for components that contributed to disaster; .............................................................................................................................................. 175
Table 25-The criteria analysis for technical perspective ..................................................................................................................................................... 176
Table 26-Decision map in terms of P.F and RBD ..................................................................................................................................................... 176
Table 27-The Criteria analysis from operational perspective .................................................................................................................................. 178
Table 28-Decision map in terms of MTTR and MTBF .............................................................................................................................................. 179
Table 29-Range of values for production cost loss ..................................................................................................................................................... 181
Table 30-Range of values for maintenance cost ..................................................................................................................................................... 181
Table 31-Decision map in terms of maintenance cost and production loss cost .... 182
Table 32-Components A, B, C and D with respect to their consequence of failure 184
Table 33-Components A, B, C and D with respect to their likelihood of failure .... 185
Table 34-Decision map in terms of consequence and likelihood of failure .......... 185
Table 35-Rule number one fires out for blowdown drum, i.e. VHC ................. 188
Table 36-CMMS features as function of price (Labib and Exton, 2001) .......... 201
## Table of figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>The variation of failure, reliability and hazard function with respect to time during infant failure (Barlow and Proschan, 1975)</td>
<td>34</td>
</tr>
<tr>
<td>Figure 2</td>
<td>The variation of failure, reliability and hazard function with respect to time during random failure (Barlow and Proschan, 1975)</td>
<td>35</td>
</tr>
<tr>
<td>Figure 3</td>
<td>The variation of failure, reliability and hazard function with respect to time during wear out failure (Barlow and Proschan, 1975)</td>
<td>35</td>
</tr>
<tr>
<td>Figure 4</td>
<td>The Weibull Shape factor</td>
<td>35</td>
</tr>
<tr>
<td>Figure 5</td>
<td>The hazard function during different pattern of failures represent a Bathtub Curve (Barlow and Proschan, 1975)</td>
<td>36</td>
</tr>
<tr>
<td>Figure 6</td>
<td>The example of logic diagrams in FTA when a fire protection system fails (Isermann, 2006)</td>
<td>44</td>
</tr>
<tr>
<td>Figure 7</td>
<td>The possible results of expert’s subjective judgement for two machineries. The red circles represent the machineries positions</td>
<td>84</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Fuzzy logic surface results deal with component that located in the borders of different criticality</td>
<td>84</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Cost and Safety as input to fuzzy model</td>
<td>99</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Cost membership functions in fuzzification phase</td>
<td>100</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Safety Membership functions in Fuzzification Phase</td>
<td>100</td>
</tr>
<tr>
<td>Figure 12</td>
<td>The defuzzification membership function for CMP implementation</td>
<td>101</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Fuzzy logic surface results for identifying criticality level of each equipment in asset</td>
<td>103</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Hierarchical structure of selecting the most appropriate maintenance strategy</td>
<td>104</td>
</tr>
<tr>
<td>Figure 15</td>
<td>AHP modelling for BP case study: The Maintenance decision Making Problem</td>
<td>105</td>
</tr>
<tr>
<td>Figure 16</td>
<td>The relative importance of one criterion with respect to other criteria to find out the best maintenance alternative</td>
<td>106</td>
</tr>
<tr>
<td>Figure 17</td>
<td>The criticality levels of equipment in the plant in terms of cost and safety</td>
<td>107</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Sensitivity analysis results obtained from AHP, it provides the relative importance of one criterion with respect to others in terms of different alternatives</td>
<td>108</td>
</tr>
<tr>
<td>Figure 19</td>
<td>The dynamic sensitivity of criteria and alternatives for Machine “A”</td>
<td>109</td>
</tr>
<tr>
<td>Figure 20</td>
<td>Sensitivity analysis results obtained from AHP for Machine “B”</td>
<td>110</td>
</tr>
<tr>
<td>Figure 21</td>
<td>Illustrates the process of operation and maintenance strategy review</td>
<td>112</td>
</tr>
<tr>
<td>Figure 22</td>
<td>The hierarchical view of setting vision for maintenance management</td>
<td>113</td>
</tr>
</tbody>
</table>
Figure 23-Presents the best performance achieved by Shell to increase MTBF on 300 pumps

Figure 24-Illustration of ISOM unit in BP Texas City disaster (Labib, 2014) ................................. 119
Figure 25- Illustration of the fluid level with respect to time (CSB, 2007) .............................. 121
Figure 26-Illustration of safety values release due to the high pressure (CSB, 2007) .... 122
Figure 27-Illustrates the directions of flammable liquid towards ignition sources (CSB, 2007) ......................................................... 124
Figure 28-The Proposed Strategic Decision Making Model ................................................... 134
Figure 29-Strategic dimensions of the proposed SDMM ......................................................... 138
Figure 30-Structure of fuzzy logic for criticality-w.r.t-Safety-Perspective ................................. 141
Figure 31-MFs defined for likelihood of failure ................................................................. 142
Figure 32-MFs defined for consequence of failure .............................................................. 142
Figure 33-Illustrated the inputs and outputs for safety ......................................................... 143
Figure 34-The criticality level with respect to safety .......................................................... 143
Figure 35-Fuzzy surface result for safety perspective ............................................................. 144
Figure 36-Structure of fuzzy logic for criticality-w.r.t-Technical Perspective ......................... 147
Figure 37-MFs defined for pattern of failure ........................................................................ 148
Figure 38-MFs defined for machine impotence w.r.t RBD ................................................ 148
Figure 39-Illustrated the input and outputs for technical perspective ................................ 149
Figure 40-The criticality level with respect to technical perspective ..................................... 149
Figure 41-The fuzzy logic surface results for technical perspective ........................................ 150
Figure 42-Illustrates the input that has been considered for operational perspective .......... 153
Figure 43-MFs defined for machine impotence w.r.t Failure Frequency ............................... 153
Figure 44-MFs defined for machine impotence w.r.t downtime ........................................... 153
Figure 45-Illustrated the input and outputs for operational perspective ............................. 154
Figure 46-The criticality level with respect to operational perspective .................................. 154
Figure 47-The fuzzy logic surface results obtained for operational perspective ..................... 155
Figure 48-The fuzzy inputs for financial perspective ........................................................... 157
Figure 49-MFs defined for machine impotence maintenance cost ........................................ 158
Figure 50-MFs defined for machine impotence production cost loss .................................... 158
Figure 51-Illustration of inputs and outputs for financial perspective .............................. 159
Figure 52-The criticality output with respect to financial perspective .................................. 159
Figure 53-The fuzzy surface result for financial perspective ............................................... 160
Figure 54-The structure of strategic fuzzy logic model for overall criticality ....................... 162
Figure 55-The overall criticalities membership functions .................................................... 169
Figure 56-The hierarchical view of strategic decision-making for selecting maintenance
strategy .............................................................................................................................. 171
Figure 57-The Expert Choice view for defining SDMM strategy implementation............. 172
Figure 58-Illustrated the decision surface result obtained for the criticality level from a technical perspective........................................................................................................ 177
Figure 59-Decision surface result from an operational perspective .......................... 179
Figure 60-Decision surface result obtained for criticality level from a financial perspective ........................................................................................................................................................................... 183
Figure 61-Decision surface result obtained for criticality level from a safety perspective . 186
Figure 62-Comparing the relative importance of different criteria for blowdown drum before failure ........................................................................................................................................................................................................... 190
Figure 63-The relative importance of cost versus safety before failure ...................... 190
Figure 64-Priorities of different perspectives from the asset manager’s point of view..... 191
Figure 65- AHP results for implementing maintenance strategy before failure........... 191
Figure 66-Best maintenance strategy to be planned preventive maintenance for blowdown drum with culture of cost-cutting............................................................................................................ 192
Figure 67-Relative importance of safety versus cost after failure ............................. 193
Figure 68-Best maintenance strategy for blowdown drum after failure ..................... 193
Figure 69-Efforts at data collection, data analysis and decision analysis..................... 200
Figure 70-Selection and classification of published papers........................................ 207
Figure 71-The number of papers published in top 5 journals .................................... 210
Figure 72-The percentage of papers published w.r.t the number of dimensions contributed ........................................................................................................................................................................... 212
Figure 73-The effort of research with respect to four perspectives ............................. 213
Figure 74-The percentage paper published in these three levels ............................... 214
Figure 75-The alignment of aims and objectives with research questions................... 232
ABSTRACT

Over the last century, there has been growing interest in changing the approach to maintenance management. The current practice for selecting critical equipment and making a decision on the most appropriate maintenance strategy is perceived to have serious limitations, principally because it lacks decision analysis.

Due to the complex nature of decision-making in maintenance management, different models have been developed for selecting critical equipment. However, many of these models considered maintenance management as operational concern and ignored the strategic concerns of maintenance management.

This thesis builds upon earlier works on decision-making for selecting critical equipment and maintenance strategy. It sets out to construct three hypotheses by introducing evidence from a comprehensive literature review, case study analysis and in-depth interviews.

The thesis focuses on artificial intelligence and multi-criteria decision-making techniques (i.e. Fuzzy Logic and Analytical Hierarchy Process) to bridge this gap. It proposes a strategic decision-making model in maintenance and asset management for selecting critical equipment and deciding on a maintenance strategy.

The novelty of model is to propose an approach in which maintenance strategy can be applied based on the equipment criticality while not making a trade-off between safety and cost but rather to combine the concern of safety with financial, operational and technical perspectives. The model provides an opportunity to consider safety as the first priority.

The research output suggests that existing criticality assessment methods for optimising maintenance delivery have limited value and are suffering from a lack of strategic decision analysis. Multi-criteria decision-making tools could be used to improve decision-making of criticality assessment methods and hence maintenance strategy implementation.

The validity of the proposed strategic decision-making model was tested through case study analysis and in-depth interviews. The results suggest that a strategic decision-making model could have a significant impact on improving safety, reliability and operational availability.

The strategic decision-making model would enable asset managers to track the consequences of their decisions whilst dealing with maintenance. It is also an effective tool in the hands of a maintenance department to convince their asset managers to make a maintenance investment.
DECLARATION

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.
COPYRIGHT STATEMENT

i. The author of this thesis (including any appendices and/or schedules to this thesis) owns certain copyright or related rights in it (the “Copyright”) and he has given The University of Manchester certain rights to use such Copyright, including for administrative purposes.

ii. Copies of this thesis, either in full or in extracts and whether in hard or electronic copy, may be made only in accordance with the Copyright, Designs and Patents Act 1988 (as amended) and regulations issued under it or, where appropriate, in accordance with licensing agreements which the University has from time to time. This page must form part of any such copies made.

iii. The ownership of certain Copyright, patents, designs, trade marks and other intellectual property (the “Intellectual Property”) and any reproductions of copyright works in the thesis, for example graphs and tables (“Reproductions”), which may be described in this thesis, may not be owned by the author and may be owned by third parties. Such Intellectual Property and Reproductions cannot and must not be made available for use without the prior written permission of the owner(s) of the relevant Intellectual Property and/or Reproductions.

iv. Further information on the conditions under which disclosure, publication and commercialisation of this thesis, the Copyright and any Intellectual Property and/or Reproductions described in it may take place is available in the University IP Policy (see http://documents.manchester.ac.uk/DocuInfo.aspx?DocID=487), in any relevant Thesis restriction declarations deposited in the University Library, The University Library’s regulations (see http://www.manchester.ac.uk/library/aboutus/regulations) and in The University’s policy on Presentation of Theses.
DEDICATION

I dedicate my thesis to my parents who have been supporting me from the beginning of my life. I also dedicate this work to my wife for her endless supports, kindness, and encouragement.
ACKNOWLEDGEMENTS

First and foremost I would like to express my profound gratitude to my mother, my father, my wife and my sisters for their endless supports especially during my education in the University of Manchester.

My special thanks to my supervisor, Dr. Moray Kidd and his invaluable guidance and the support he has extended to me during the period of my study in the University of Manchester.

I would like to thank Mr. Tom Lenahan, Mr. Paul Wheelhouse and Mr. John Harris who sheared their industrial experience in asset management. Their valuable comments improved the standard of present study. I also thank Mr. John Harris and Prof John D Andrews who shaped my views on maintenance and asset management. The author wish to thanks all the teaching staff of reliability engineering and asset management in the University of Manchester specially Pro.Ashraf Labib who sheared his academic knowledge in operational research and asset management and also thanks to staff of the MACE department.

I am highly grateful for those who have provided opportunities for me to have industrial and academic interviews namely Dr. Joe Barnes, Mr. Tom Lenahan and Mr. Paul Wheelhouse and Dr. Moray Kidd.

Last but not least, I would like to tanks all my teachers from primary, secondary and high schools that motivated me for higher education. And also thanks to the university lecturers who encouraged me to have a hardworking personality. My special thanks to Mr. J. Fathalinejad who taught me how to read, write and speak English.
CHAPTER 1 – Introduction

1.1-Research Background
There have been different approaches to maintenance and asset management during last century. This moves from reactive to preventive maintenance strategy and from predictive to proactive maintenance strategy. From the early 1930s to the early 1960s, the maintenance followed a ‘fix it when it breaks’ policy. Initially, asset managers thought of maintenance as an added cost to the plant with no return on investment (ROI). In other words, all equipment was expected to wear out and consequently the failure was considered inevitable.

In fact, industrial plants used to have no maintenance strategy rather than simply being reactive. They followed a run to failure strategy, and the philosophy of maintenance was to operate the equipment until it failed and then repair it or replace components. This strategy is still followed in some industrial plants even to this day but due to potential environmental consequences and safety concerns this strategy is no longer acceptable. However, this strategy is useful when there is no opportunity for a return in maintenance investment. Therefore, it might be acceptable if and only if the consequences of failure have been analysed and are controlled appropriately to ensure safe operation.

The second generation of maintenance refers to the era when scientific technology and engineering concepts had developed substantially and when longer equipment life, higher machinery availability and lower costs were expected. The Weibull distribution and bath tub curve were used to model failures.

From the early 1960s until the early 1990s, asset managers started to expect to ask for longer asset lives, higher availability and lower cost. This vision from the top level of organisations forced executive managers to change their attitudes towards
maintenance. This resulted in deploying more creative maintenance, such as time based maintenance or fixed time maintenance.

In recent decades, from the 1980s up to the present, maintenance expectation has been growing. The maintenance management was supposed to deal with concerns such as better production quality, higher availability and reliability, thus ensuring longer asset lives and, much more importantly, greater safety. As a result of some catastrophic incidents in industrial plants, the importance of maintenance management became more strategic, especially when the consequence of such incidents destroyed the reputation of a company and in the worst case scenarios, such as the Deepwater Horizon oil spill, disqualified companies from continuing with their business in the area (Reider-Gordon et al., 2013). This highlights how crucial it is to look at the maintenance management from a more strategic level rather than just operational.

Many industrial plants have tried to address this by implementing appropriate software packages such as Computerised Maintenance Management Systems\(^1\) (CMMS), SAP maintenance programme and many others. Such packages are able to deal with huge quantities of data, thus providing opportunities for better maintenance management. Even though packages like CMMS have some advantages, such as integration, scheduling, resource planning and reduction of breakdowns that can influence the efficiency of plants, but there are some limitations that related to the decision analysis phase of such packages.

Some studies on CMMS (Labib, 2008) have shown that there are serious deficiencies in these packages. Vast amounts of capital are spent on data collection to be used for

---

\(^1\) CMMS is a widely-used software package which creates a database for the maintenance operation of an asset. It is also called enterprise asset management.
input into these hungry systems and at best the systems provide information that decision-makers already know or offer a calendar job activity. However, more essential information is required to enable decision-makers to analyse the trends of assets from a strategic perspective. The term ‘black hole’\(^2\) was coined by Labib to describe this (2004). He states that such packages like CMMS are incapable of delivering such a decision analysis phase for decision-makers.

There have been attempts in the literature to fill the gaps of decision analysis in maintenance management (W.Labib, 2004, Labib, 2008) with a decision-making framework for implementing maintenance strategies looking at the maintenance problem from a more operational perspective. (Fernandez et al., 2003) discuss a decision support system for maintenance management based on downtime and frequency of failure. Moreover, (Yuniarto and Labib, 2005) discuss the lack of optimum control of unreliable machines using fuzzy logic.

More recently, a new concept of decision analysis was proposed by (Labib, 2014) based on learning from failures using multi-criteria decision-making (MCDM) tools such as analytic hierarchy process (AHP) and techniques such as fault tree analysis (FTA) and reliability block diagram (RBD).

Even though some researchers have made a reasonable contribution to the development of an appropriate decision-making framework for selecting critical components in assets and hence implementing a maintenance strategy, it appears that current research looks at a maintenance problem from a more operational level than a strategic level. In fact the criteria that have been considered in such models seem to focus on operational concerns. For instance, (Triantaphyllou et al., 1997) propose an

\(^2\) A black hole is a star which has such a gravitational force that it absorbs anything in the air without emitting anything at all (W.Labib, 2004)
AHP model which considers four criteria, i.e. availability, reliability, reparability and cost as the most important elements for maintenance strategy selection which might be reasonable for manufacturing industry but not for nuclear industry. (W. Labib, 2004) proposes a decision analysis model which considers only two criteria, i.e. downtime and frequency in a decision-making process which are the main concerns of production and maintenance managers. However, in actual oil refinery plants or upstream assets these criteria might not necessarily be enough to cover the concerns of asset managers. On the other hand, some researchers argue that many more criteria need to be considered in actual oil refinery plants. (Bevilacqua and Braglia, 2000) applied AHP to select best maintenance strategy for an integrated Italian gasification and combined cycle plant; more than 12 criteria were considered in the AHP model. It is important to note that, as the number of criteria increase the subjective judgement of decision-makers increases, and this introduces a degree of uncertainty due to the complex relationships between criteria.

1.2- Problem statement

23\textsuperscript{rd} of July 1984 Illinois Union oil refinery explosion (Groves, 2006), 5\textsuperscript{th} of May 1988 Louisiana Shell Refinery explosion (Hancock, 1990), 6\textsuperscript{th} of July 1988 Piper Alpha disaster (Drysdale and Sylvester-Evans, 1998), 23\textsuperscript{rd} of March 2005 Texas City Refinery explosion (Holmstrom et al., 2006), 20\textsuperscript{th} of April 2010 deepwater horizon oil spill in the gulf of Mexico (Ray Sanchez, 2014). There have been many reports (CBS, 2006 and many others) which discussed the reasons behind these disasters such as cost cut policy, unsafe operation, using inappropriate criticality assessment methods, inaccurate decisions toward maintenance strategy and many others.

Pareto’s Law of Maldistribution (Hardy, 2010) holds that 80% of consequences of many phenomena stem from 20% of causes in other words 80% of downtimes come
from 20% of machineries. Many industrial plants in energy sector will use its own criticality assessment methods, which identify the criticality of components from a safety and operational perspective, and so can be used to decide on a maintenance strategy. However, many failure reports claimed that there is a link between failures and the components that have not been considered as been critical during criticality assessment methods. Recently study of (Qi et al., 2015) used a fuzzy logic-based criticality assessment system (FCAS) to establish an effective maintenance strategy and obtain more realistic and accurate results during criticality assessment of an industrial plant. However the proposed approach fail to address the safety on its own and still simply adds up the cost and safety elements with different impact factors, which represent the level of priorities for maintenance cost, business impact and safety.

The main issue is whether current criticality assessment method and decision-making on maintenance strategy considered the strategic concern maintenance management and look at the safety on its own. Is it possible to improve such methods from a strategic perspective?

1.3- Research Aims and Objective
There has been growing interest in changing the approach to maintenance management over the last century. During the last decades, many researchers have looked at the maintenance problem from a more operational level. A few research centres have focused on maintenance management from a more strategic level by combining reliability engineering and risk management knowledge. These have tried to establish partnerships between universities and industry to improve the quality and level of research (D.N.P. Murthy, 2002).
The first phase of research in this study investigates how artificial intelligence can be utilised to identify the most critical parts of assets from a strategic perspective. It will be followed by the second phase of study which discusses how MCDM tools should be utilised for deciding on maintenance strategy.

One way to be innovative in selecting critical parts of assets and deciding on maintenance strategy is to learn from failures by focusing on decision analysis of asset management, not only for physical assets but rather to reflect how the organisational culture of cost-cutting or safety as the first priority could influence the overall performance of maintenance management.

The purpose of this research is the following:

1. To identify the process in which decision-making for selecting critical equipment can be improved from a strategic perspective.
2. To investigate what criteria required to be taken into account for selecting critical parts of industrial assets while using case study analysis and in-depth interviews with experts in oil and gas industry.
3. To identify the current gap in decision analysis of asset and maintenance management
4. To propose a Strategic Decision Making Model (SDMM) that enables decision-makers to improve asset management.
5. To suggest a hybrid approach that provides feedback for the decision-maker to understand how continues improvement can be achieved through the decision-making process.
1.4-Research Questions
1. What criticality assessment methods are used in the oil and gas sector for selecting critical parts of assets? What are the strengths and weaknesses of current packages used for asset management? Is there any gap in strategic decision analysis in such packages?
2. What are the main criteria that are required to be considered for selecting the most critical items, components, units or processes in oil and gas industrial plants?
3. How could criticality assessment methods be improved from a more strategic perspective?
4. How to implement MCDM tools (i.e. Fuzzy AHP) to achieve continued improvement in maintenance management?

1.5-Hypothesis
Hypothesis 1: Maintenance management is suffering from a lack of strategic decision analysis.

Hypothesis 2: Existing criticality assessment methods for optimising maintenance delivery have limited value.

Hypothesis 3: MCDM tools could be incorporate to improve decision making of criticality assessment method and hence maintenance strategy implementation.

1.6-Limitations
1. This research investigates maintenance management from a more strategic perspective. Therefore, most of the interviewees work at the top levels of organisations as senior managers. They have limited time and in most cases refuse to be interviewed by a PhD student. Another limitation is time. There
is a 3 year limit for carrying out data collection. This can be considered the most difficult part of the research.

2. Data collection was carried out during Master classes in the field of risk management, reliability analysis, availability improvement, maintenance strategy, asset management, turnaround management, maintenance origination, asset maintenance system and artificial intelligence in business management. Therefore, different experts from different levels of organisations were interviewed which might slightly differ with the view of asset managers.

3. During the development process of SDMM, it was very difficult to access real data from oil and gas industrial assets to run the proposed SDMM. Therefore, the validation of the model was mostly carried out by in-depth interviews with managers of oil and gas consulting companies who are more familiar with the concerns of asset managers and also with the qualitative feedback of experts in the field of maintenance management.

4. Moreover, case study analysis considered to present the usefulness of SDMM. However, due to some confidentiality aspects of failures limit data were presented in such reports in which the hypothetical scenarios have been used to present how the model can be implemented in an industrial plant.

5. Last but not least, because the strategic concept is long term in its nature, it requires a lengthy period of time to analyse the performance of the model across industry. This is almost impossible within a PhD timeframe.
1.7- Summary of research in 1st, 2nd and 3rd years
The first year of research focused on standardisation practices used by the oil and gas industry. It focused on understanding what risks and reliability principles are currently applied in oil and gas operations.

The second year of research focused on the concepts of asset and maintenance management, arguing how continues improvement could be achieved through a maintenance management approach. Consequently, in the second year of research several training courses were attended in the disciplines of maintenance strategy, risk, reliability and availability, asset management and artificial intelligence. This led to identifying the gap in maintenance management.

In the third year, an SDMM approach was developed to address the gap of decision analysis for maintenance and asset management. It was also shown how the continues improvement should be achieved whilst implementing the SDMM. The model was developed during in-depth interviews with experts in the field of maintenance and asset management to ensure it meets the requirement of an industrial plant in the oil and gas industry.

1.8-Thesis Structure
The research consists of 7 chapters as follows:

- Chapter 1 gives a general background on maintenance management and introduces the problem statement to the research. It is followed by the aims and objectives that the present study will cover. The research questions are recognized and the relevant hypotheses are introduced in accordance with the research aims and objectives.
- Chapter 2 discusses the concept of reliability, availability and maintenance followed by a review of the techniques used for maintenance management. It
then continues by identifying the gaps and problems in relation to the
decision-making phase of maintenance and asset management with a review
of literature in this field.

➢ Chapter 3 discusses available research methodology in management science
and then considers the research methodology that has been selected for the
current study. Both primary and secondly data collection processes are
discussed and the reasons of using artificial intelligence and AHP have been
provided.

➢ Chapter 4 discusses the case study analysis that has been evaluated during the
last two years of research whilst attending Master classes and training
programmes such as artificial intelligence, maintenance strategy, condition
monitoring, maintenance organisation, risk, reliability, maintainability,
turnaround management, design for reliability and asset management. This
led to the development of the SDMM.

➢ Chapter 5 discusses how SDMM has developed. Its development process is
explained through both case study analysis and interview results and then a
justification is provided for the use of fuzzy logic and AHP for the
development of SDMM.

➢ Chapter 6 is divided into two parts. The first part highlights the contribution
of this research by identifying the current gap in the literature where large
number of papers were analysed and criticised based on their weaknesses and
strengths in decision-making for implementing maintenance strategies. Of the
114 reviewed, 58 papers were classified in terms of their contribution to
different levels of maintenance and asset management.
Moreover, the second part of this chapter critically reviews the developed SDMM based on interviews. The validity of the model is discussed through in-depth interviews with experts in the field of asset and maintenance management both from academia and industry.

- Chapter 7 includes recommendations for future research. Possible improvements to the model are discussed based on the feedback of the experts in the field. More importantly, the industrial proposal provided for implementing SDMM to real oil and gas industrial plant. In addition, contribution to knowledge is summarised followed by a list of academic attempts and publications.
CHAPTER 2 Literature review

2.1- Introduction
In this chapter, the comprehensive literature review focuses on the concepts of risk, reliability, decision analysis, criticality assessment method, maintenance strategy and maintenance management. It aims to identify potential improvements to models developed for asset management by focusing on multiple disciplines, such as safety, reliability, availability and maintainability, whilst achieving a cost benefit solution.

Section 2.2 discusses the concept of reliability, availability and maintainability whilst elaborating on reliability assessment methods such as Weibull Analysis. The comprehensive review of current literature in reliability studies provides a deeper understanding of the reliability concept.

Section 2.3 discusses approaches to learn from failures such as Fault Tree Analysis (FTA), Reliability Block Diagram (RBD), Risk Priority Number (RPN), Failure Mode and Effective Analysis (FMEA).

Section 2.4 briefly discusses different types of maintenance strategy, i.e. Run to Failure (RTF), Fix Time Maintenance (FTM), Condition Based Monitoring (CBM), and Design out Maintenance (DOM).

Section 2.5 discusses decision analysis concepts and its tools and techniques, such as artificial intelligence (AI) technique (i.e. Fuzzy Logic) and the multi-criteria decision-making tool – Analytical Hierarchy Process (AHP) – that has been considered for this research.

Most importantly, section 2.6 aims to identify the gaps in the decision-making phase of maintenance management by reviewing the most important papers in the literature which highlight the need to develop the strategic decision-making model (SDMM).
A comprehensive literature review has been carried out to compare and contrast the published papers. This suggests that there is a gap in the literature that could be filled by strategic decision analysis for maintenance strategy implementation.

2.2-Reliability, Availability, Maintainability Concepts

2.2.1-Introduction to RAM

The aerospace industry and some military application were pioneers of considering reliability evaluation techniques which has been followed by process plant, chemical plants and oil production platforms in which a failure in such plants causes deaths, environmental pollution and production loss. The concept of Reliability, Availability and Maintainability are closely linked to each other.

It is important to discuss the relationship between reliability, availability and maintainability. Imagine there is request for reliability improvement, then the maintenance activity need to increase within a plant that means increasing down time which results in reducing availability. In other word if the operation of maintenance in a system has not been taken into account accurately, it could negatively influence the availability of a system and results in reducing the reliability of a system.

As far as industrial managers used to focus on production rate rather than reliability therefore many industrial plants have been suffering from inappropriate maintenance strategy. However, nowadays it has been understood that it worth to invest in reliability to avid catastrophic failure of facilities which leads to unsafe operation, huge amount of loss in production, waste of time, money and many others.
2.2.2- Reliability definition and Concept

Reliability can be defined as “The probability that an item will perform its required function in the desired manner under all the relevant conditions and on the occasions or during the time intervals when it is required so to perform” (Green and Bourne, 1972)

Similarly (THOMPSON, 1999) describe reliability as “Reliability is the probability that a component, device or system will continue to perform a specific duty under prescribed environmental conditions for a given time”. In which environmental condition can refer to any elements like vibration, dirt, temperature, etc.

Considering the above definitions, the term probability introduces a concern in maintenance management. One could argue that reliability is focusing on a component within the system or system in itself. While there is degree of uncertainty involved in each operation that has got nothing to do with component performance.

To be more specific, the reliability of the systems is depends on reliability of different variables i.e. hardware, software, operation condition and human performance. A Reliable sophisticated equipment and facility could become easily unreliable with untrained hands and poor communication (Paté-Cornell, 1993) in which unsuitable hands will deliver poor maintenance those results in unreliability of system which has not been taken into account.

The reliability analysis has been developed more for physical assets i.e. considering computational techniques and advanced mathematics modelling specially for the complex systems to identify failure characteristic of a system and analysing causes of failure component. The result of such reliability analysis used to provide an opportunity for appropriate maintenance practices.
2.2.3- Reliability Calculation

To getting involve with more mathematical concepts behind evaluation of the reliability, assume the total number components \(N_o\) has been tested during time \((t)\) few number of components failed \((N_f)\) and the number of components survived known define as \((N_s)\) meaning that \((N_o) = (N_f) + (N_s)\), where the reliability of the component would be defined as the probability of the surviving components in during the time \((t)\) therefore the reliability, and the failure of component can be defined as following:

The probability of component surviving refers to \(R(t) = \frac{N_s}{N_o}\)

The probability of failure refers to \(F(t) = \frac{N_f}{N_o}\)

Where \(R(t) + F(t) = 1\), and the hazard rate \(h(t)\) known as mean failure rate or instant failure rate.

\[
h(t) = \frac{dN_f}{dt} \times \frac{1}{N_s} \quad \text{Equation 1}
\]

Where the term \(\frac{dN_f}{dt}\) is total number of failure per unit time, which is not the sufficient quantity since this failure rate is depend on the number of components meaning that different testing with different number of component would deliver different result to avoid such a problem to evaluate the reliability of system the following concept should be carry on:

\[
F(t) = \frac{N_f}{N_o} = 1 - R(t) \quad \text{Equation 2}
\]

Therefore \(R(t) = 1 - \frac{N_f}{N_o}\) \quad \text{Equation 3}
Now with differentiation of both side the following formula can be obtain:

\[
\frac{dR(t)}{dt} = \frac{dN_f}{dt} \times \frac{1}{N_o}
\]

Equation 4

Now substitute \( h(t) \) instead the of \( \frac{dN_f}{dt} \) the following formula can be obtain:

\[
\frac{dR(t)}{dt} = -h(t) \times \frac{N_o}{N_o} = -h(t) \times R(t)
\]

Equation 5

With rearranging the above equation and integrating from both sides the reliability equation can be found as follow:

\[
\frac{dR(t)}{R(t)} = -h(t) \, dt
\]

\[
\int_1^R \frac{dR(t)}{R(t)} = - \int_0^t h(t) \, dt
\]

\[
R(t) = e^{-\int_0^t h(t) \, dt}
\]

Equation 6

As it can be seen in the integration limit, the component reliability is assumed to be perfect therefore it account to be \( R = 1 \) at \( t = 0 \).

2.2.4-Weibull Analysis

Weibull analysis was originally coined by Weibull in 1937 (Weibull, 1951). The objective of the Weibull analysis is to predict the failure behaviour within a system. It is based on statistical analysis of historic failure data. It includes plotting failure data and interpreting it accordingly and also it found to be a cost effective approach for replacement strategies and forecasting spare parts.

In addition this method is also useful for maintenance planning and controlling which provides recommendation to maintenance mangers in response to service problem. There are two main advantages for Weibull analysis i.e. first, it propose
reasonably accurate approach for failure forecasts and failure analysis with extremely small samples. Secondly it suggests a useful and simple graphical plot for the failure data.

In order to get familiar with Weibull analysis it is important to introduce the term Probability Distribution Function (PDF) is also called Probability density function. This will be used in data analysis to predict the behaviour of the component in a system. In other words PDF investigates the probability of failure over time period.

Usually histogram is used to create PDF based on the life data analysis. In fact the Weibull is general form of PDF that model the time to failure phenomena. There are three main types of failure introduced by Weibull analysis.

The first type refers to infant failure or running in failure. This type of failure usually introduce at early age of components where the component might failed because of inappropriate installation or operation. As figure-1 presents the failure rate reduce with respect to time.

![Graph of f(t), R(t), Z(t) vs t]

*Figure 1-The variation of failure, reliability and hazard function with respect to time during infant failure (Barlow and Proschan, 1975)*

he second type is known as random failures in which failures are subjected to any random failure within useful life of components, the follow picture present this view.
Lastly, the third types of failure refer to wear out which is due to the age of component. As the following figure represent, as the time increase the hazard rate increase it means that the reliability of component decrease as the useful life of components decrease.

- $\beta < 1.0$ represent running in failure
- $\beta = 1.0$ represent random failures (independent of age)
- $\beta > 1.0$ represent wear out failures
Therefore the whole life hazard rate profile can be illustrated as the following known as “bath tub curve”.

![Diagram of hazard function phases](image)

**Figure 5**-The hazard function during different pattern of failures represent a Bathtub Curve (Barlow and Proschan, 1975)

### 2.2.5-Availability

The availability of item can be defined as ratio of time that item is capable of operation to the sum of the down time and up time.

\[
\text{Availability} = \frac{\text{Total uptime}}{\text{total up time} + \text{total downtime}}
\]

\[
\text{Availability} = \frac{\text{Mean time to failure}}{\text{Mean time to failure} + \text{Mean time to repair}}
\]

As it is illustrated in the above definition, there are two terms i.e. working and failed state. It is important to know that the same result might be generated with steady state availability. For instance the item which runs continuously for 4 day and it needs one-day refurbishment would generate availability of 80 % which is the same availability of the machines that runs 20 minutes and required to be stop for 5 minutes.
To be more specific, it is importance to consider the context in which availability need to be discussed, for instance inherent availability discussed the availability from design perspective where the terms Mean Time Between Failure (MTBF) and Mean Time To Repaired (MTTR) considered in availability calculation. While from operation perspective, the operational availability considered the term Mean Time Between Maintenance (MTBM) and Mean Down Time (MDT). In fact MTBM includes all corrective and preventive activities whereas MTBF address only failures and MDT considered all times and delays associated with system being down for corrective maintenance while MTTR account for repair time only.

\[
Ai = \frac{MTBF}{MTTR+MTBF} \quad \text{Equation 7}
\]

\[
Ao = \frac{MTBM}{MTBM+MDT} \quad \text{Equation 8}
\]

Availability of a system or item can be increased if the MTBF increase and/or MTTR decrease. Similarly, operational availability would be increase if MTBM increase and/or MDT decrease.

Moreover it is important to note that availability will be calculate in terms of any random time during operation whereas reliability need to be evaluate in specified running time. For instance in order to calculate overall availability of a system that has N components and all are installed in series, the system availability can be calculate by following formula during random time of system operation.

\[
As = A1 \times A2 \times \ldots \ldots \ldots \times An \quad \text{Equation 9}
\]

And Unavailability of a system will be calculated as:

\[
Us = 1 - As \quad \text{Equation 10}
\]
2.2.6-Maintainability

Maintainability can be defined as: “*The measure of the ability of an item to be retained or restored to specific conditions when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources at each prescribed level of maintenance and repair.*” (Chen and Cai, 2003)

The maintainability of system or component which is failed refers to probability that such a system can get back to its operable condition, under the stated condition within the stated period of time using prescribed resources and procedures. (Sutton, 2010b)

Maintenance traditionally known to be a technical job that made by new technicians it used to do with design, however maintenance defines as “*All activities that are intended to retain or resort the product to specified condition*” (Chen and Cai, 2003)

Maintainability needs particular attention from design stage of plant; there have been always barriers in terms of maintainability because most of the plants have been design with people who have almost no communication with people that actually running the facilities. Therefore the lack of communication has been identified as one of the main barriers in effective asset management.

In fact the lack of communication is not only limited to people who are designing the facilities and people who operating plan. The lack of communication exists within different level of organisation and people who operation plant, for instance the Piper alpha disaster is result of inadequate communication between the shifts personal in the plant (Labib, 2014).
In fact, there is missing link between two distinct cultures in which one group focus upon building facilities and other group focus on using facilities and there has been always a miss understanding between costs versus value. One of the main questions that need to be asked during reviewing the design process is that “Can this design be cost-effective operated and maintained”.

2.3-Current approach to learn from failures

2.3.1- Criticality Assessment Method

Criticality assessment methods are used to identify critical components within industrial plant that require particular attention. Such methods mainly focus on the equipment that its failures have significant effect on production loss, environment and safety.

The qualitative scoring scheme used to be considered for criticality analysis which assesses consequences and likelihood of failure. As the nature of each industrial plant might vary from one to another therefore different factors might require to be consider. For instance some industries might have particular concern about safety like nuclear, whereas manufacturing industry such as automobile production line might not require considering the same criteria for assessing criticality of components.

The criticality assessment methods are used to identify critical equipment’s for cost effective investment on maintenance strategy. In fact the most expensive maintenance strategy used to be implemented for the most critical components. These methods usually consider factors such as current situation of equipment, cost of maintenance, ease of maintenance, downtime and safety.
The procedure usually requires both maintenance and production teams work together and analyse the block diagram and flowsheet of the plant and assign rating to component subjectively in which the assessment includes utilities and services. Both paper or computer based scoring scheme could be use within industrial plant that usually includes two level high and low review, which are optimistic and pessimistic values.

It is worth mentioning that such criticality analysis will help areas such as prioritising work in predictive maintenance, operating instructions and maintenance procedures, reliability centre maintenance and helping spares procurement decisions.

However, there is some important weakness around such criticality assessment methods; one could argue that it is very probable that different maintenance or production managers provide different values for the importance of criteria which results in different criticality outcome, in fact it is really difficult for maintenance staff or expert to provide correct numerical evaluation (Braglia et al., 2003). In other words the value provided with operation and maintenance technicians are the qualitative judgement which are only the guesses at the best, therefore such approach appears to be less precise and might require improvement. Chapter 4 will elaborate more in detail in current approaches in criticality assessment method used in oil process plant and addressed how these weakness can be address though SDMM.

2.3.2-Failure Mode and Effective Criticality Analysis

Failure Mode and Effective Criticality Analysis (FMECA) originated as formal methodology in the 1960s (O'Connor and Kleyner, 2011). It is a qualitative reliability techniques in which systematically analyse the each possible failure mode with respect to their probability of occurrence. FMECA known to be as one of the
hazard analysis techniques, which is a bottom up approach and could be a powerful approach if it links with Fault Tree Analysis i.e. top-down approach. FMECA analysis has been taken into account within complex industries which the failure of its components could result catastrophic incident (Sutton, 2010a, Moubray, 1991).

2.3.2.1- FMECA Steps
In order to implement FMECA in the process plant, there are several steps that need to be considered. The first step refer to functional analysis where hierarchical scheme produce to list the subsystem and parts of the system according to their function in the plant.

Secondly, all possible failure modes need to be identify and accordingly criticality assessment will be carry out to measure the level of risk for each faults. The factors such as delectability, severity and probability of a failure will be considered in the assessment.

Thirdly, the model of failure will be rank with respect to the criticality assessment method, and in the next step the appropriate decision and action will be consider towards the high risk problems. Lastly, the appropriateness of the action will be evaluated and the decision will be update based on the revise risk analysis. (Braglia et al., 2003)

2.3.2.2-Two ways of FMECA execution
Mainly, there are two different way of executing FMECA i.e. developing a Risk Priority Number (RPN) or calculating a Criticality Number (CN). In which depending on the type industry as being manufacturing, automotive, energy sector, one method might preferred to the other.
2.3.2.2.1-Risk Priority Number (RPN):
The linguistic term will considered to give the values for the chance of the failure being undetected known as “D”, the severity of its failure effects represent as “S”, and the chance of failure- mode occurrence shown as “O”. Then the value of RPN will be obtained as the multiplication of these three factors.

\[ RPN = D \times S \times O \]

RPN is in favour of manufacturing industries such as automotive production line. Because RPN approach is less expensive than CN, and it is believed that RPN is quicker than CN.

One the other hand, one of the main drawbacks of this approach is that it relies on the linguistic term which have been provided with maintenance expert or technicians. In fact such values could be only expert’s guesses. However, there have been different approaches in the literature to address such concerns i.e. implementation of fuzzy logic (Sharma et al., 2005b, Kutlu and Ekmekcioğlu, 2012) utilised fuzzy logic to address such concern.

2.3.2.2.2-Criticality Number (CN):
Criticality Number calculation is procedure which indicates failure effect probability, failure mode ratio, part failure rate and its operating time, in which the overall CN will be calculated as multiplication of these values. In fact, such method is more appropriate in high risk industries such as nuclear, chemical and aerospace industries. In addition, such CN is much more expensive than RPN.

2.3.2.3-FMECA Limitation
Nowadays, FMECA is one of the most popular reliability analysis techniques for many industrial plants; however after its implementation it faced to some drawbacks. Firstly it only considers three criteria i.e. severity which is mainly about safety,
chance of failure and chance of non-detection and FMECA has nothing to do with financial concerns. Secondly, it is difficult to give the exact numbers for each criterion. This results in evaluation of intangible quantities and provides linguistic values for factors such as “chance of failure” that presents a critical problem regarding the liner relationship between failure probability and provided scores therefore the mathematical formula which is a simple production of each criterion is questionable.

Most importantly, one could argue that maintenance managers would like to give different weightings for the importance of each criterion while FMECA does not provide such opportunity of weighting criteria (Braglia et al., 2003).

2.3.3-Fault Tree Analysis (FTA)
In 1961 the concept of fault tree analysis developed by H Wastson in Bell Telephone laboratories (Watson, 1961, Lee et al., 1985). It provides logic diagram which investigates the relationship of system failure and causes that results in failure. The logic diagram consists of events and gates. The analyse focuses on the failure mode and break down the event to reach specific causes. There are two main types of logic gates Known “AND” & “OR” in which an “AND” gate will be used in the logic diagram if all the input events occurs at the same time in order to reach the output event whereas an “OR” gate will be used if at least one or more input event occurs in order the TOP event occur.

The top events could be explosion, safety system does not work, total loss of production or any other concern. The figure 6 is an example of logic diagrams which breakdown a top event as if fire protection system fails.
2.3.3.1-Fault versus Failure

It is important to discuss what distinguish fault from failure and what the differences between these terms are? Basically, the term failure refer to the item in which its ability to perform require function is terminated whereas the fault is refer to the state of an item characterised by inability to perform the requested function. In other words, failure is an event while fault is a state.

To be more specific, failures are obtained from the failure modes in which they are linked directly to the reason that cause failure within the boundaries of equipment in itself whereas faults investigate the behaviour of equipment with respect to other component. For example if switch doses not close on time within a system because of inappropriate function of other component, this will not refer to the switch failure but it is fault which is an unsatisfactory state. In other words not all faults are failures but all failures are faults.

It is worth mentioning that, in the Fault three analyses, the faults of all equipment is not modelled while only those failure mode or faults that resulted to the top event will be included into the model. (Čepin, 2011)
2.3.3.2-Objectives of Fault Tree Analysis
One of the reasons that author decided to discuss FTA techniques in this chapter was its application within the industry. FTA has been implemented into many industrial plants and its objective can be summerised as following:

1. It identify the most important component within the system according to its reliability function; and hence
2. Identifying the most critical area of the system that requires particular attention from maintenance implementation
3. It assess the failure probability of system function
4. Provide an opportunity to compare the different design for a system
5. It improve the knowledge about maintaining the system and its behaviour while enhancing the documentation of systems (Čepin, 2011)

2.3.4- Reliability Block Diagram
Before reliability evaluation of any system, it is necessary to understand the operational relationship of all elements within a system, therefore the presentation of such relationship can be capture if the following questions answer appropriately:

- How these elements functions? And;
- How such elements effect system operation?

Reliability Black Diagram (RBD) is a mean of representing the relationship between components within a system. It determines how each items must operate successfully in order the system deliver its indented function.

Reliability block diagram can be consider as complementary of fault tree analysis and usually can be obtain from FTA. In order to draw RBD with respect to FTA the idea is to transform every “AND” gate to the parallel structure and every “Or” gate to the serious structure. There are 5 golden rules which enable as to draw RBD from FTA discussed in(Labib, 2014).
• Rule Number 1: Every OR gate in an FTA is equivalent to a series structure is an RBD
• Rule Number 2: Every AND gate is an FTA is equivalent to a parallel structure in an RBD
• Rule Number 3: The Number of basic events (Circles) in the FTA is equal to the number of boxes in the RBD
• Rule Number 4: Order (Sequence) does not matter
• Rule Number 5: Start from the top of the FTA when attempting to draw reliability block diagram.

2.3.5-System Types

There are mainly two types of systems i.e. mission oriented systems and continually operated system. The duty of the mission oriented systems is that to continue to function without failure till the mission reach to the end of its expected duty, while individual component failure is allowed if and only if the mission of the system continues to function on time. Repairing or replacement of the fail component is possible only if there were no interruption of the systems mission.

To be more specific, there are two subcategories of mission oriented systems, first categories refers to those systems which would be checked totally before the operating phase starts, It needs the confirmation to declare that the system would be reliable during its operation time. The great example could be an airplane where the take-off would not be occurs until all the subsystems have been checked properly ensuring that the time of the mission is less than of failure time of any component or subsystems.
Second categories refers to systems where there would be an inactive phase in which system getting into its operating stage and considering to be functioning during the mission time while expecting an random idle time which cause a failure of system. The protection system could be a great example in which remains inactive until a random fault occurs, meaning that the appropriate alarm action and controlling action take place if and only if random faults occur.

Second type system can be defined as continually operated systems in which require replacement or repairing activities during the system operation. It is very important that techniques require for recognition of restoration process to be understood, learn and perform accurately. Imagine there is an electrical distribution system which suffer from failure due to bad weather conditions that causes interruption of supply energy to certain customers, therefore considering required techniques for restoring system into operating state is a critical stage for life of the system.

For assessing such behaviours of these types of systems, not only different techniques are required, but also different measure and criteria are required as well (Billinton and Allan, 1992, Roy Billinton, 1983).

Elaborating more on why such systems fail, as it mentioned earlier there is a missing link between two distinct cultures in which one group focus upon building facilities and other group focus on using facilities. In fact such missing link dose exists in different level of asset and maintenance management with people having different culture of running the asset which results in catastrophic incident. In chapter 4, the analysis of BP Texas city disaster discussed such a missing link in more detail. Please note that present study is focused on the second type of system where there is
a need of continued operation of system such as offshore or onshore oil and gas industrial plant.

2.4- Maintenance Strategy
Mainly, there are two main trends in maintenance strategy. The first trend is focusing on physical assets where a technique such as Reliability Centred Maintenance (RCM) has been introduced in the literature, and secondly type is when there is need to invest on nonphysical assets like human where technique such as Total Productive Maintenance (TPM) is more highlighted. (Geraghty, 1996)

Different types of maintenance strategies will be discuss briefly in the following which focus on reactive to proactive concepts of maintenance strategies i.e. Operate to failure, Fix time maintenance, Skill level upgraded, condition based maintenance and design out maintenance. (Kelly, 1997, Márquez, 2007, Labib, 2014)

2.4.1- Operate To Failure (OTF)
As it is name suggests, it means that no action will be taken until the operation stop as result of failure of component in other words no action is going to be taken into account to prevent failure. It also called run to failure (RTF). This method is only cost effective if the failure result was negligible in terms of safety and production lost. In more general term it refers to as reactive maintenance strategy or run to failure approach (Labib, 2008).

2.4.2- Fix Time Maintenance (FTM)
In this strategy regular interval will be carried out to detect any possibility of problem with machinery. The first level action would be to decide whether to repair or replace. Generally the difficulty of this strategy could be divided in to two levels. The first level is refers to those problems which are not complicated and operators are able to understand what is a problem and who is in charge to fix it and when the
maintenance action can be carry out. However the difficult level appears when with the problem cannot be detected through inspection. Therefore it is required to ask for an expert to carry out investigation in order to find out what a problem is and how it should be solve.

2.4.3- Skill Level Upgraded (SLU)
This strategy is appropriate for equipment that usually have high frequency of failure but when it occurs it does not make a big problem or downtime for the system and it takes a short time to repair. The maintenance of these kinds of machinery is not the difficult task. It usually requires a professional expert to come over the plant and repair the equipment. In fact by arranging an appropriate training programmes the operator’s skill can be upgraded easily in which they will be enable to deal with such failures without requiring an expert to gets involve for maintaining the equipment (Labib, 2008).

2.4.4- Condition Based Maintenance (CBM)
British Standard defined Condition Based Maintenance as “the preventive maintenance initiated as a result of knowledge of the condition of an item from routine or continues monitoring” (BS 3811, 1984)

In other words condition-based maintenance is a technique that inspect and monitor condition of components periodically to identify degradation rates of relevant components. Different methods have been used such as visual inspection, sensors, sampling of lubricant products, and many others to avoid catastrophic damage to critical equipment and permit continued operation of critical machinery. Oil and Gas industry was one of the pioneering industries to implement CBM in which techniques such as vibration analysis and infra-red thermography were considered especially in process plant. In order to perform successful CBM for machinery there
are number of element in which need to be taken in to account i.e. reliable detection, correct diagnosis and dependable decision making.

It is important to note that this maintenance strategy is required when the frequency of breakdown is low but when it occurs it cause big downtime. For more information please refer to (Holroyd, 2000) and (Brashaw, 1998).

2.4.5-Design Out Maintenance (DOM)
In contrast with other maintenance strategies, this strategy aims to eliminate the cause of maintenance instead of mitigating or avoiding failures. Generally, this strategy is considered as the last option in which some experience of operation is carried out and other maintenance strategy are providing expensive or useless solution. Therefore this strategy would be implemented if and only if other maintenance strategies performance was unsatisfactory for an item to provide sufficient reliability. This strategy will be considered when the engineers observe that an item is not working and stop performing more than expected in which they feel the machine will need to be structurally modified.

2.5-Decision Analysis
It is vital to understand the importance of any decision and it perspective within an organisation, there are different level of decision within any organisation, more significant decision are those that dealing with corporate planning\(^3\) and aggregate planning\(^4\) master planning until it reach to intermediate lower level planning and

\(^3\) Corporate planning is a systematic approach to clarifying corporate objectives, strategic decision making and checking progress toward objectives.

\(^4\) Aggregate planning (AP) in business is defined as the process of development, analytics and maintenance of a schedule for the business' overall operations. It is usually medium range in nature, lasting anywhere from three to 18 months.
process control. Decision levels move from physical type towards operational, tactical and strategic, its frequency reduce while it significant improves this means that decision is function of time in which as the decisions become more strategic its results cannot be obtains in short period of time. For instant the investment decisions would take years and even for decades to get its results whereas training decisions results in months or years and shift decisions in the operational level results in months and minutes.

There have been many different techniques which can be implement for decision analysis in operational research. (Mohamad Ashari AliasI, 2008) has done extensive literature review of multi criteria decision making (MCDM) and it application and it was believes that there are two main trends in MCDM. The first trend is the one which considers Artificial Intelligent (AI) approaches in MCDM known as AIMCDM and the other trend is the one which follows the Classical operational research techniques known as CMCDM. The most popular techniques in AI was identified as Fuzzy Logic (FL), Generic Algorithm (GA), Neural Network (NN) and Expert System (ES), While Classical approaches include Analytic Hierarchy Process (AHP), ELimination Et Choix Traduisant la REalité which means ELimination and Choice Expressing REality (ELECTRE), Preference Ranking Organization METHod for Enrichment Evaluation (PROMETHEE), Technique for Order-Preference by Similarity Ideal Solution (TOPSIS), and Analytic Network Process (ANP). It was argued that across 113 papers in MCDM the most popular methods used were Fuzzy logic or the combination of Fuzzy logic with other methods like AHP in which research in management was the most popular area of research that used MCDM for selecting, ranking, and evaluation of alternatives and
research in manufacturing ranked second popular sector using MCDM for evaluation.

In order to investigate the effectiveness of AI and MCDM techniques for current study, chapter 5 comprehensively discussed how these methods utilised for developing strategic maintenance decision making model (SDMM) in which AI has been implemented in criticality assessment method and MCDM used for selecting the best maintenance strategy. It is worth mentioning that the term MCDM is also present in similar abbreviation such as MCA i.e. Multiple Criteria Analysis, MCDA i.e. Multi-Criteria Decision Analysis, MDDM i.e. Multi-Dimensions Decision Making, MADM i.e. Multi-Attribute Decision Making.

2.6- Critical review of maintenance and asset management

2.6.1- Identifying current gaps in the literature
Even though some researchers make a reasonable contribution to developing a decision-making framework for selecting critical components and hence deciding on the maintenance strategy, it seems that current research looks at maintenance problems from a more operational perspective rather than a strategic one. For instance, (Triantaphyllou et al., 1997) proposed an AHP method to consider four criteria: availability, reliability, reparability and cost as the most important elements for maintenance strategy selection. However, the method seems to be not appropriate for the oil and gas industry as the effect of safety has not been taken into account.

On the other hand, other researchers argue that many more criteria need to be considered in real-life oil refinery plants. (Bevilacqua and Braglia, 2000) applied AHP to select the best maintenance strategy for an integrated Italian gasification and combined cycle plant. More than 12 criteria were considered in an AHP model. However, as the number of criteria increased the subjective judgment of decision-
makers will increase, and this introduced a degree of uncertainty due to the complex relationships that they had with each other.

(W.Labib, 2004) proposed a decision analysis model known as a Decision-Making Grid (DMG) which focused on historic failure data and considered only two criteria, i.e. downtime and frequency in the decision-making process which are the main concerns of production and maintenance managers.

This section is aimed at identifying the gaps in the decision-making phase of maintenance management by reviewing the most important papers in the literature which highlight the need to develop a SDMM.

(Udayumar et al., 2009) argue that each individual business unit, system or plant might require its own specific way of assessing the criticality. They argue that assessing the criticality of two similar business units and/or plants in the same industry might not be fair because of the need to consider the relative importance of risk factors etc. In addition, the culture of the organisation and the qualitative approach to assessing the risk factors might cause there to be different criticality approaches.

2.6.2-Background of other literature review papers
The literature review of maintenance management has so far been limited to the papers that look at the concept of maintenance management from an operational perspective. (Garg and Deshmukh, 2006) analysed 142 papers and systematically categorised issues in maintenance management ranging from maintenance performance measurement and information systems to maintenance scheduling, maintenance techniques and maintenance optimization models. More recently, (Ahuja and Khamba, 2008) reviewed 180 papers on Total Productive Maintenance
(TPM) and discussed a different range of issues in the field. (Simões et al., 2011) reviewed 251 papers on maintenance performance measurement. The paper suggests different themes in the development of maintenance performance management. The themes focus on effective utilisation of the human factor management, information system support and maintenance resources and a conceptual framework proposed towards maintenance performance management from an organisational and operational perspective.

The present study discusses the existing gaps in the literature by reviewing the most important papers in maintenance management based on the concerns of strategic management; these highlight the need to develop a SDMM.

2.6.3- Classification of published papers
Managing an industrial asset from an operational perspective and prioritising high financial returns over the short-term could damage long term value creation (Porter, 1991). Such a concern highlights the need to look at maintenance management from a strategic perspective rather than an operational perspective.

As discussed earlier, there are different ways in which research into maintenance management has been classified in the literature. The present study aims to analyse maintenance management from a strategic perspective. Therefore, the contribution of (Kaplan and Norton, 2001) into strategic management has been taken into consideration in this study as they introduced the concept of Balance Score Card (BSC) on four different levels, i.e. learning & growth, internal business perspective, and customer and financial perspective.

The published papers were classified in terms of their contribution to each of these perspectives whilst identifying their contribution to different decision levels of
maintenance management. Consequently, the contributions of papers were classified based on their impact in terms of being theoretical, methodological or applicative. The reason behind this classification is to highlight the need for research in strategic decision-making for maintenance management and encourage practitioners and researchers make efforts to fill the current gap in the field.

Even though there have been many useful attempts both in academia and industry to develop maintenance management models, as presented in the discussion chapter both academia and industry are well behind what is expected from strategic maintenance management. Bridging this gap provides an opportunity to move towards a new generation of maintenance, i.e. towards self-maintenance and self-repair capability (Urnes et al., 1990, Rhea et al., 2001).

2.6.4- Critical commentary on published papers

Comments on Decision Making Grid (DMG)
Even though in actual practice there are established methods to identify critical parts of assets which focus on safety and production concerns, analysis of failure reports of disasters shows that industries such as nuclear and oil and gas have been suffering from a lack of decision analysis (Labib, 2014). There have been attempts in the literature to establish decision analysis in maintenance management. For example, (Fernandez et al., 2003) discussed a decision support system for maintenance management; (Yuniarto and Labib, 2005) discussed the lack of optimum control of unreliable machines using fuzzy logic; (W.Labib, 2004) proposed a decision-making grid (DMG) for selecting maintenance policy by using two criteria, MTTR and MTBF, as the basis of decision-making for maintenance strategy selection; (Burhanuddin et al., 2011) argued that DMG is incapable of dealing with cost and suggested a cost analysis for DMG. More recently, (Ishizaka and Nemery, 2014)
considered the effect of two other criteria in addition to MTTR and MTBF, i.e. spare parts cost and bottleneck loading using ELECTRE-SORT, and discussed that the proposed DMG is incapable of adding unlimited criteria into its decision-making phase.

It is important to state that decision-making at the operational level is structured, and as the decision-making rises to higher levels in the organisation it becomes more unstructured as the objective of decision-makers become more varied. It depends how attribute performance matches with decision maker objectives. (Feng and Lai, 2014) propose an approach to consider the objective of decision-makers from a strategic perspective in which the model was developed during solving a problem in Strategic Freight Forwarder Selection of China Southern airlines. They claimed that the model will provide a consistency coefficient that enables managers to evaluate the robustness and reliability of the group decision. In fact, it makes a contribution to filling the gap between individual opinion and group opinion. The proposed approach could accommodate uncertainty in linguistic terms, numerical values and interval numbers.

(Wee and Widyadana, 2013) proposed the deterioration inventory model for the manufacturing industry. The paper contributes to the operational phase as sensitivity analysis is carried out to validate the model. Sensitivity analysis shows that demand rate and production rate play an essential role in the optimal production period. Given that the demand rate is uncontrollable, the production time should increase whenever the preventive maintenance cost and time increase in order to minimise the lost sales cost. It was then argued that, as far as the nature of machine unavailability is stochastic, it is not easy to solve production rate and production uptime at the same time.
On the other hand, (Bacchetti and Saccani, 2012) investigated ten case studies in spare part management and addressed the existing gaps between practice and research. They discussed four areas where the current gap needs to be filled:

- To supplement proposed models in academia with respect to practical needs
- To encourage a knowledge and information-gathering process in industry
- To determine contingency based managerial guidelines
- To improve spare part management by developing integrated approaches

The research illustrates spare part classification, inventory control and demand forecasting as part of maintenance management which need to be analysed from a strategic perspective.

(Amado et al., 2012) proposed an approach for evaluating the performance of asset management by combining BSC and data envelopment analysis (DEA which is a non-parametric technique) from different perspectives, i.e. learning and growth, internal processes and financial aspects. The research focuses on particular company and proposed a strategic map for the maintenance department. The model suggests that as the amount of equipment under maintenance increases; the return on investment improves appropriately. In fact, the research confirms that maintenance needs to be looked at from different perspectives, i.e. a strategic perspective as well as an operational one.

Last but not least, it is worth to mentioning that Barata et al. (2002) proposed an approach that monitors deterioration continuously by implementing the Monte Carlo simulation. The model was first deployed on a non-repairable single component and then it was considered for a multi-component repairable system. The main purpose
of the research was to improve maintenance optimisation by minimizing cost. It aims to find out the thresholds of maintenance interventions.

It is worth mentioning that the gamma process has been used as a maintenance optimisation approach to model stochastic deterioration since it was introduced in early 1975. The gamma process has been identified as useful for maintenance decisions due to its ability to model the temporal variability of deterioration and to determine optimal inspection intervals. Van Noortwijk (2009) reviewed the simulation, approximation and estimation methods used in gamma process and an inspection and maintenance model based on gamma deterioration process was introduced which focused on the technical perspective only.

**Maintenance Strategies need to align with corporate Strategy**

Over the last few decades, the perception of maintenance has been changing from a necessary evil to a value added activity. (Van Horenbeek and Pintelon, 2014) state that competitiveness of manufacturing companies in the market is dependent on the productivity, reliability and availability of equipment which cannot be achieved unless the maintenance manager understands the maintenance process fully by utilizing maintenance performance indicators (MPI) and maintenance performance measurement (MPM). Many papers suggest maintenance performance measures and related indicators but none of the proposed frameworks suggest a strategy for selection of relevant MPI that can be used to cope with maintenance objectives for a specific business context. It has been argued that practical MPM that helps maintenance managers to select relative MPI from strategic perspective need to establish a link between corporate strategy and manufacturing. The analytic network process (ANP) model was proposed and applied in several case studies to deal with this concern.
(Pintelon and Gelders, 1992) discuss decision-making for maintenance management from a theoretical perspective. The framework proposed includes three stages. Firstly, it focuses on the system design aspect of maintenance management, specifically the type of industry, organisational responsibilities, and maintenance management philosophy and production control system. Secondly, a discussion on maintenance objectives and policies was carried out in the context of decision-making for maintenance management in planning and control. Thirdly, a maintenance tool kit in computer support and failure modelling was discussed. It was concluded that operational research is one of the best ways to improve the quality of maintenance management where it provides an opportunity to quantify the qualitative judgement and subjective decision-making in maintenance management.

It is crucial to state that there have been many uncertainties involved in decision-making for risk and asset management problems due to the subjective judgement of managers. In operational research, stochastic modelling was developed to deal with such uncertainties in actual practice. This may refer to classical approaches to inference. Bayesian, fuzzy or any AI approaches are used to identify the optimum PM intervals and/or optimum replacement time for a system. For instance, (Percy, 2002) proposed a suitable form of reliability model to investigate how to reflect expert opinion in such modelling with the implementation of the Bayesian approach. However, the proposed model is inappropriate when there are little data available and also this research only contributed to decision analysis of maintenance management from a technical perspective.

(Murthy and Asgharizadeh, 1999) discuss how it is possible to implement game theory to decide the most appropriate options for outsourcing the maintenance. The theoretical model proposed that determines the optimal strategy based on price
structure, number of maintenance providers and number of service channels. The paper helps the manager to select the best maintenance provider options and it contributes to the managerial level of maintenance management.

In addition, a multi-criteria model for auditing a predictive maintenance programme (PMP) is proposed by (Bana e Costa et al., 2012). A multi-criteria decision analysis (MCDA) model aimed to measure performance of the predictive maintenance programme. The model was implemented in a hospital. The results indicate deficiencies in PMP and also suggest corrective measures for continues improvement.

Last but not least, (Wang, 2002) conducted a survey to develop the theoretical concept of maintenance policy for deteriorating systems in which the relationship between maintenance policies was addressed and also the maintenance policy was compared and classified. The maintenance policies were identified as opportunistic maintenance policy, group maintenance policy, preparedness maintenance policy, mixed age policy, reference time policy, repair number counting policy, repair time limit policy, repair cost limit policy, sequential preventive maintenance policy, failure limit policy, periodic preventive maintenance policy, block replacement policy, random age replacement policy and age replacement policy.

**Strategic maintenance management**

Even though there have been some papers published to deal with maintenance management whilst considering four strategic dimensions, the contribution of such papers has been made from a theoretical perspective. For instance, (Crespo Marquez and Gupta, 2006) reviewed the maintenance management concepts which introduce a framework to establish various functions in terms of maintenance management in different levels of business activities, i.e. operational, tactical and strategic. The
approach for maintenance management was analysed in-depth from three main perspectives: relationship management, maintenance engineering and information technology. They set out how to align maintenance management in three levels with all activities.

Moreover, a theoretical maintenance management framework was proposed whilst considering the different strategic perspectives discussed earlier. (Márquez, 2007) discussed KPI issues in three organisational levels in terms of maintenance management. It was argued that the performance of maintenance management in a strategic level should convert the business priorities into maintenance priorities whilst establishing a long-term maintenance plan to recognise the gaps in maintenance performance as well as assess the maintenance performance. More analysis was carried out in regards to the process level known as tactical in which there is a need for resource allocation to perform a maintenance plan, i.e. test equipment, material, skills, etc. It was then explained that the maintenance task is carried out at a component level known as the operational level. When maintenance is executed it delivers feedback to examine whether the maintenance objective appropriately aligned with strategic decisions. In order to improve the reliability of the decision-making process for both expert judgements and performance quantification, it is essential to develop a model that supports realistic KPI assessment (Gu et al., 2012).

(Kaplan and Norton, 2001) discuss the possibility of linking measures and performance objectives with strategy by implementing BSC and a strategy map. They state that a scorecard should be implemented in order to align the management system and process to the strategy. They then argue that a strategy focused organisation needs to adhere to five main principles.
The first principle is that it is essential to define the strategy in operational terms in which it can be understood and translated from an operational perspective. The second principle is that even though different levels of an organisation have their own culture, language and bodies of knowledge, they all need to be aligned for a specific strategy. The third principle is an acknowledgement that senior managers cannot implement the strategy by themselves, everyone contributes to strategy implementation. The fourth principle is that the performance will measure against plan periodically. In most of the industrial plants, apart from an annual strategic planning meeting, there is no meeting held with senior managers to discuss the strategy periodically. Therefore, it is important to make the strategy a continuous processes where there is an opportunity to test the strategy and get feedback, and then update the strategy based on the reports and available budget. The final principle is termed ‘Mobilize leadership for change’. This highlights the need for active involvement and ownership by the executive team in addition to the tools and processes in the first four principles. BSC indicates that projects need to be considered as a changeable process rather than a matrix project. BSC initially concentrates on creating a momentum and mobilisation to enable the process to be launched. Once it is mobilised, the new performance model will be installed and the management system changes. Over several years, the new management model evolves. This means that new processes and cultural values will be formed into a new system for management which can be identified as a strategic management system.

During the last decade, the University of Queensland created a research group on reliability engineering and risk management to investigate maintenance management from a strategic perspective. This has collaborated closely with industry to
implement strategic approaches towards maintenance management. (Murthy et al., 2002) discussed the two key elements of strategic maintenance management including activities that are required to achieve a strategic maintenance management approach.

It was discussed that the approach towards maintenance management should not only focus on mathematical modelling for quantitative analysis but also on the qualitative judgements that provide continued improvement solutions from an overall business perspective. In fact, almost no model has been published to combine these perspectives.

The maintenance management concepts were reviewed by (Crespo Marquez and Gupta, 2006), and were used to introduce a framework to establish various functions in terms of maintenance management in different levels of business activities, i.e. operational, tactical and strategic. The approach for maintenance management was analysed in-depth from three main perspectives, i.e. relationship management, maintenance engineering and information technology. This indicates how to align maintenance management from three levels with all activity from a theoretical perspective and not any methodological and/or applicative approach proposed to combine these perspectives.

**Complexity of maintenance management**

The complexity of maintenance management has been discussed in a number of books, such as Asset Management Excellence: Optimizing Equipment Life-Cycle Decisions (Campbell et al., 2010); Strategies for Excellence in Maintenance Management (Campbell and Reyes-Picknell, 2006); and Maintenance Resources Management (Shenoy and Bhadury, 1997).
There are many elements involved in maintenance management. For instance, it is necessary to investigate the required activity to implement maintenance strategy, i.e. maintenance control (costs, inventories, materials, and quality oriented management), maintenance organisation (project administration, work measurement, standards and work design) and maintenance planning including scheduling, capacity, maintenance workload forecast and workload (Duffuaa et al., 1999).

The complex nature of MPM was discussed by (Parida and Kumar, 2006). It was argued that for a successful implementation of MPM it is necessary to involve all employees. It was explained that in order to align the objective outcome at an operational level with corporate strategy both internal and external maintenance effectiveness should be analysed and an appropriate relationship between internal measures (causes) and external measures (effects) should be established which is a very complex task. They argued that even though Overall Equipment Effectiveness (OEE) is a useful approach to measure internal effectiveness, measuring the external effectiveness is very complex. The research introduced the concept that both internal and external effectiveness can be evaluated appropriately from a theoretical perspective. The findings suggest that there is a gap in maintenance and asset management which is mainly associated with the absence of strategic decision analysis for selecting critical components and deciding on appropriate maintenance strategies.

Due to the increasing trend of competitiveness in communication and information technologies for industrial enterprises, asset managers are demanding more comprehensive capabilities from these packages to enable them to improve targeted performance by mastering and better understanding the operating system. This is because asset managers need certain data which they can consider as input to their
decision-making to identify the best strategies and accordingly allocate resources appropriately to achieve the best expected performance. However, there are some concerns that such enterprises need to deal with. First and foremost is to assess how realistic and reliable the approach is as each system considers certain assumptions to decrease the complexity of analysis which might not be realistic because it does not represent the real situation of operating system. Secondly, development of such packages could be very time-consuming and expensive. (Medina-Oliva et al., 2015a) proposed an approach to deal with such challenges where the methods investigate the dependability function within industrial systems in order to evaluate the performance of both production and maintenance based on the maintenance strategies applied.

In order to perform the policy issued by the enterprise maintenance system, the activities play an essential role in dealing with availability, product quality, performance efficiency and many others. Hence, it is the responsibility of the maintenance manager to decide on the most appropriate maintenance strategy and break down the strategic goal of organisation to operational targets whilst integrating the operational performance with the strategic level. Such a break down will introduce the concept of KPI which enables decision-makers at different levels (operational, tactical and strategic) to negotiate and discuss the overall situation of business with the same language.

The combination of communication tools and modern information process is referred to as the Tele-service. (Yu et al., 2003) stated that such a technology support is still far from providing an AI environment for maintenance decision-making, especially decision-making that not only needs to exchange information between asset managers and clients but also requires negotiation and cooperation over contradictory and/or complementary knowledge. (Yu et al., 2003) argued for the
need to move towards e-maintenance and provide an artificial environment, especially decision-making that requires expert inputs. Therefore, a problem orientated multi-agent based e-service (POMAESS) was developed to bridge this gap. The model focused on service maintenance problem-solving which is based on a decision support function. A negotiation protocol is developed for a prototype system.

Last but not least, (Weber et al., 2012) discussed the ability of the Bayesian network (BN) with respect to techniques such as Petri nets, Fault three and Markov chain. It was discussed that BN has advantages compared to other decision-making tools in the context of the research. For instance, its modelling capability is very user-friendly due to its compact and graphical approach and BN represents multi-modal variables; it can update the calculation according to the evidence. Interestingly, it can also accurately evaluate the probability occurrence of an event as well as making predictions and diagnoses.
2.7-Conclusion
The concept of reliability, availability and maintainability has been discussed through Weibull analysis, FTA, RBD, RPN and etc. And also the approaches to different maintenance strategy have been explained briefly.

The current gaps in the decision-making phase of maintenance asset management have been discussed through the review of literature. It has been highlighted that there is a need to consider maintenance management from a strategic perspective.

It was argued that currently there is a gap in the decision analysis phase of maintenance and asset management which could be related to criticality assessment methods as well as to deciding on a maintenance strategy. The evidence in the literature suggests that AI and MCDM techniques can be utilised to improve decision-making in maintenance management.

Last but not least, this chapter highlights the importance of strategic decision-making in maintenance and asset management and the findings suggest that it is essential to move towards strategic decision-making for selecting critical components and hence deciding on a maintenance strategy. In fact, a critical review of literature in maintenance management suggests that decision-making for criticality assessment method and maintenance strategy implementation needs to be enhanced from a more strategic perspective.
CHAPTER 3 Research methodology

3.1- Introduction
This chapter briefly discusses research methodologies that have been used in management sciences. The philosophical view of the researcher behind the selection of the most appropriate research method for the present study is then discussed. This is followed by information on the motivation behind qualitative exploration within maintenance and asset management research. The reason for using case study analysis will also be explained in detail. The motivation of conducting semi-structured interviews and structured interviews has been presented. It was explained how such interviews enable the researcher to develop the SDMM and also validate the usefulness of proposed model.

Last but not least, the reason behind implementing fuzzy logic and AHP in the proposed model will be discussed and also the advantages and disadvantages of fuzzy AHP approach highlighted. This will include a justification for using both fuzzy AHP approaches.

3.2- Approaches to research methodology in management sciences
There have been different types of research methodology in the management sciences. Depending on the purpose of the research, different approaches have been implemented to uncover solutions to a problem presented in the literature.

However, regardless of the application of the study, research in management can be categorised into two types: context-based research and purpose-based research. The first type can be considered as pure research used to understand and elaborate on the process of management and business, and this is mainly undertaken by academics; the second type is referred to as applied research which provides a solution for managers and deals with critical issues that arise in practice. Usually, people based
in industry, companies and organisations undertake this type of research (Saunders, 2007).

Once the nature of the research is identified then the research methodology needs to be established. Research methodology mainly refers to the procedures and plans that span the decisions from a broad assumption to specific methods for analysis and collecting data which lead to identifying what design should be considered to carry out research. According to (Saunders, 2007), there are three main types of research designs. These are summarised over the next few paragraphs.

The first method is considered qualitative research as it tries to understand specific information about behaviours, values, opinions, etc. This method is a useful approach when there is a need for the interpretation of a complex situation. To be more specific, this method aims to penetrate deep into the research perspective. It mainly includes interpretive approaches towards the problem statement and prioritises data contribution of existing information regarding research questions.

The second type is quantitative research which focuses on numerical data analysis. It measures quantities to develop theories or confirm hypotheses by using different methods, such as surveys and questionnaires. A mainly quantitative research considers assumptions about testing theories deductively, generalising and replicating the findings, controlling for alternative explanations, and building in protections against bias (Creswell, 2009).

The last type of research is considered as the mixed method of both quantitative and qualitative approaches. This aims to minimise the weakness of each method and improve the overall strength of research. In recent years, researchers have begun to consider the mixed method as a more productive approach to generating findings.
This is exactly what is considered for the present study with additional emphasis on qualitative exploration.

The next stage after indicating the most appropriate research method is to recognise strategies of inquiry which provide for a specific direction on the procedures in research design. There are a number of factors that influence the methods used in research strategy: the extent of existing knowledge, the research aim and objectives, the research questions, the availability of resources, etc. According to (Creswell, 2009, Saunders, 2007), these strategies can be summarised as: case study, experiment, survey, action research, archival research, grounded theory and ethnography. The following list briefly summarises each strategy and its application.

- **Case Study:** This approach is most appropriate when there is a deep understanding of context and it discusses a programme, process, activity or event in depth.

- **Action Research:** The purpose of action research is to learn from the results of scientific knowledge and considers it actively in the heart of research. It is most appropriate when there is a need for experiences from practitioners to build a relationship between researchers and practitioners.

- **Survey:** This approach is more appropriate when there is a need to highlight a fact which can be understood by ordinary people and/or any sector. This might be appropriate when a large amount of data exists. The main purpose of this method is to determine the quantitative description of opinions, attitudes and trends by evaluating data coming from a sample population.

- **Experiment:** The aim of this approach is to study casual relationships and links between different facts. This approach might be used to test a
hypothesis or theory. Experiment is most appropriate for natural sciences with bounded problems, and it relies on the findings of a small group.

- **Grounded Theory:** The main purpose of this approach is to generate theories based on the data. In other words, with the aid of data and the process of conducting research, appropriate theories will be generated. It is most appropriate for researchers who are interested in predicting human behaviours.

There have been many other research methods discussed in the literature which has not been mentioned above as they are not relevant to the context of the present research. As far as the current study focuses on maintenance management so a comprehensive problem statement has been defined as the first step and accordingly the key questions which are capable of answering the expected finding have been identified. The answers to the proposed questions have been categorized into different approaches: exploratory, descriptive and/or explanatory studies, which will be discussed next. Last but not least, the contribution of knowledge for the present research has been obtained by implementing a mixed approach (qualitative and quantitative).

### 3.3- A post positivist Epistemological foundation

In operational or management research, the philosophical view of the researcher plays an important role in designing a research method to test his/her proposed model or hypothesis. As such, it is vital to understand whether the epistemological view of the researcher is relativist or positivist.

A relativist essentially believes that values and facts are inseparable. In other words, relativists are those who argue that there is no absolute truth or validity because all observations are rooted in cultural, linguistic and perceptual aspects of the observer’s
personality. In contrast, a positivist believes ‘that facts and values are distinct, and that scientific knowledge consists almost exclusively of observable facts’ (Audi, 1999).

Eisenhardt (1989) states that positivism is a necessary starting point for the development of a theory or hypothesis which can be tested and generalized across a setting. This is exactly what the present study intends to do.

The proposed model will be tested through data collection from industrial reports and qualitative interviews with consultancy companies. It is important to highlight that there is a higher likelihood of uncovering larger truths when data are gathered from multiple sources. Again, this is exactly what happened in the present study. It was perceived that artificial intelligence (AI) and multi-criteria decision-making (MCDM) could effectively improve decision-making in maintenance management. Hypotheses were also tested through case study analysis.

However, this is not to say that the developed model or the findings could be implemented in any plant through a ‘one-size fits all’ approach. In fact, the proposed model can be modified according to the requirements of the industry or specific company.

The strategic concern of any company or industrial plant might vary from one to another or there might be other concerns that asset managers want to include or exclude. The proposed model is a good starting point and can be altered depending on the needs of each plant. The novelty of model is about how to combine the views of middle managers simultaneously to arrive at one comprehensive solution.
For instance, for companies that deal with the nuclear industry like DuPont or many other Japanese and European companies who wish to make safety as their first priority, the view of safety managers requires particular attention, similar to oil and gas companies. On the other hand, there are some companies who do not need to concern themselves about safety as much as those in the nuclear industry. All this flexibility can be accommodated when the researcher defines the specific rules within the model.

One of the most challenging parts of any strategic model is its validation process because a strategic concept is long term in its nature and it is very difficult to test such a SDMM within a PhD timeframe. However, the usefulness of such a model can be tested through case study analysis where the decision of an asset manager can be traced through different scenarios such as in the culture of cost-cutting or safety.

One of the main concerns with management research is its potential for generalisation. (Schmenner and Swink, 1998) state that in management research, generalisation of results is an elusive goal in management science.

To be more specific, post-positivism holds that reality exists but cannot be explained or understood completely and that it is possible to have a better understanding of the real truth (Gephart, 2004). Similarly, other post-positivists (Guba and Lincoln, 1994) argued that ‘reality can never be fully apprehended, only approximated’.

As far as the purpose of the present research is not to make deterministic predictions or establish absolute truths to improve asset management but rather to discuss whether certain decision-making methods for identifying critical components and hence selecting a maintenance strategy can be improved through the implementation of AI techniques and MCDM tools. Therefore, a post-positivist epistemological
perspective has been adopted as the foundation for this research. In fact there is not an absolute answer while identifying critical equipment to improve asset management but rather using multi criteria decision making tools such as fuzzy logic and implementing sensitivity analysis for selecting maintenance strategy enable asset managers to learn from continues improvement and such techniques provides and opportunity to have a better understanding of real truth. This is why the current study is rooted in post positivism instead of relative rigidity of epistemological positivism.

3.4-Data Collection: Primary and Secondary data
As the term ‘data collection’ suggests, it refers to the systematic gathering of information for a specific purpose. In other words, it is a process of preparing and collecting data for a particular purpose. The basic inputs of any decision-making process are data. A well-structured decision-making process which is fed incorrect data is of little value.

There are many reasons for collecting data, such as recording and tracing the behaviours of a system to provide information to pass on to the corresponding area. Such data collection has been considered in industries, either manually or through computerised maintenance management systems. One of the main reasons that the present study is looking at data collection is to test the usefulness of its proposed model, especially when the model makes decisions for important issues.

There are two types of data that have been gathered in the current study: primary and secondary. Primary data is mainly data that has been gathered through a field investigation under the control of the researcher. In other words, it is original data accumulated for the purpose in mind. There are two types of such data: quantitative data like surveys and experiments; and qualitative data which include focus groups, individual in-depth interviews, human observation and case studies.
There are many advantages to using primary data as it addresses specific issues within the research and also its interpretation is more efficient whilst the researcher has a greater control on such data. However, there are some drawbacks for such an approach to collecting data; it is very time consuming, inaccurate results might be obtained, and multiple sources might need to be taken into account.

For the present study, the primary data collected was qualitative; a group of consultancy companies in the energy sector were contacted to arrange in-depth interviews. The purpose of such interviews was to understand decision-making processes for selecting critical equipment within industrial plants and also to investigate what criteria have been considered in decision-making and how the effect of such criteria has been taken into consideration. The primary data were mostly gathered during participation in workshops, training courses and Master classes where there was an opportunity for the researcher to arrange his interviews with lecturers and those students that had the relevant experience in maintenance and asset management.

Secondary data mainly refers to the data recorded by someone else which is reused in a different context. Such data usually require less effort and time to interpret and can be reused for a specific purpose. Secondary data are obtained from sources such as books, magazines, journals and the Internet. Even though secondary data has some advantages, such as being easy and fast to access and helpful for answering research questions, but it may well not be specifically related to the needs of the researcher or it might provide incomplete information. The present study uses many industrial case studies as secondary data which have been discussed with groups of people from industries who attended a postgraduate programme in maintenance and asset management at the University of Manchester.
This study aims to investigate the approaches to criticality assessment methods for selecting maintenance strategy so it is crucial to perform a comprehensive data collection. This should include both academic and industrial reviews. Therefore, the required information for the present study needs to be gathered from academic papers, individual interviews, case study analysis and reports generated from industry. The usefulness of SDMM can then be tested by in-depth interviews with experts in the field of maintenance and asset management.

It is important to note that the data gathered from industry was obtained from reports generated in companies to describe a process of decision making, or discovering the reasons of failures, lesson learnt conclusions and etc.

3.5- Qualitative Exploration & Development of SDMM
The research questions in the introduction chapter aimed to identify the current gap in decision-making for maintenance management. The first phase of qualitative exploration was designed to reshape this broad area of research into a relevant and workable hypothesis.

The development of a hypothesis is a dynamic process in its initial stages, especially when there is a need to have an interpretative analysis of data gathered through a literature review. Hypotheses are very likely to change over a six month period. Most hypotheses also tend not to be linear or straightforward (King et al., 1994).

The qualitative exploration was initially based on a desktop study in which relevant papers were critically reviewed and classified during three years of research. The classification of published papers in the literature provided an opportunity to understand the current gap in decision analysis for maintenance management from an academic perspective. This encouraged the researcher to investigate whether there
was a related concern coming from industry by contacting consultants and experts in the field of maintenance management. The second phase of qualitative exploration was carried out through semi-structured interviews. The questions for these were initially designed to confirm the findings of the desktop study and then continue to explore the concerns of industry.

The third phase of qualitative exploration was where the analyses of industrial reports formed the foundation of SDMM. To be more specific, the analysis of industrial reports dealt with issues like the method of selecting critical equipment for condition based monitoring, improving maintenance strategy to reduce breakdowns and also issues like lessons learnt from failures. It was argued that there should be a link in industrial plants between identifying the most problematic equipment and implementing a maintenance strategy. This led to the development of SDMM.

Once the SDMM draft was produced, the companies that owned oil production platforms were contacted. Emails were sent out to many companies seeking collaboration. However, due to the economic challenges in the oil and gas industry, namely the volatility of oil prices, many companies stopped collaborating with universities and so almost no replies were received from them about the possibility of one-to-one interviews. Therefore, an innovative approach to getting an interview was considered. Instead of contacting oil and gas companies directly, the consultant companies who worked for such companies were contacted instead. These are extremely aware of the concerns of asset managers in this industry.

Two parallel approaches were considered in order to validate the model. The first one was to contact professors in the field of decision-making for maintenance management. This provided valuable feedback on the model and some slight
modifications were proposed. Secondly, the case study analysis was used as secondary data to present how the model works in practice. In order to show how continues improvement can be achieved through the development of an asset; those case studies were selected that had suffered from a catastrophic explosion.

3.6- The Motive for Using Case Study Analysis
The case study analysis was considered in two different stages in the research: case studies that contributed to the development of the SDMM, and those that contributed to illustrating how the model works and validates its usefulness.

One of the main motivations for using case study analysis was to understand the main problems within real-world practice in maintenance and asset management. After attending Master classes in maintenance and asset management and working on the case studies in workshops, two main concerns of asset managers became apparent: the first was the concern over selecting the most critical component for investment to improve plant safety, reliability and availability; the second was the concern over deciding what maintenance strategy was appropriate for the most critical pieces of equipment.

In other words, the first type of case studies formed the foundation of the proposed model where there was a need to select the most critical components for CBM implementation within a BP oil process plant where the main concern was to obtain a cost and safety trade-off. Therefore, a decision-making framework was developed for implementing CBM techniques based on the needs of industry practice. The model was modified based on the discussions during semi-structured interviews with experts in the field of maintenance management. This will be discussed in the next section.
As far as the proposed model tries to focus on maintenance management from a strategic perspective, there are two ways to validate it. The first and most time-consuming approach is to run the model in an actual industrial oil production plant or any other industrial plant and then get feedback on the performance of the asset. This is almost impossible within a PhD timeframe because strategic concepts are long-term by their nature.

To be more specific, this means that if an asset manager decided not to accept the proposal of the maintenance department, the results might not be observed on the whole asset. This occurred in the BP Texas City disaster where the maintenance department prepared a proposal for implementing a maintenance strategy through design out maintenance for the flare system within the refinery which required $2 million investment. However, the asset manager rejected the request of the maintenance department and 3 years later the disaster happened.

Therefore, a clever way of tracking the behaviour of asset managers is to use case studies where disasters were experienced and then culture of asset managers can be tracked through the decision made towards maintenance strategy implementation. In fact the second phase of the SDMM model utilized AHP to address this issue.

3.7- The Motive for Using Semi Structure Interview
As explained earlier, semi-structured interviews were designed to consider the inputs for the proposed model whilst at the same time getting feedback on the model. Semi-structured interviews also provide an opportunity for deeper understanding of the concerns in such a decision-making process and also help the researcher to ask more complex questions. This is not possible during case study analysis where there is only limited data available. In addition, these were carried out to qualitatively
validate the approach and the criteria that have been taken into account in the current model.

3.8-Development of SDMM using Fuzzy AHP approach

3.8.1- Forming a decision making problem
Any multi-criteria decision analysis has the following main steps to form a decision-making problem in a hierarchical order: problem modelling, weight valuation, weight aggregation and sensitivity analysis.

The aim of the first step is to structure the decision problem in hierarchy order and identify decision-makers who play a key role in solving the problem so it is necessary to design the socio-technical system. The second step is to identify different alternatives for solving the problem. The third step is to identify the criteria for assessment of each alternative in which such criteria might need to be clustered in different levels of hierarchy.

The stage is to assign weighting for each criterion in order to highlight model the culture of decision makers within the asset. This stage is followed by combining the scores and weights for criterion to indicate their relative importance of each criterion from asset manager perspective.

The next step is to score the criteria and alternatives where performance of each alternative against the criteria will be evaluated. In this step, initially the consequence of each alternative is described by scoring the importance of alternative with respect to each criterion and then the consistency of judgement will be assess by consistency ratio (CR).

Last but not least, the results and sensitivity analysis are examined to look at the advantages and disadvantages of the chosen alternatives and compare the pairs of
alternatives. Any possible new options are studied that might be better than the initial options to improve the accuracy of the model. A question that arises is whether other preferences or weights affect the overall ordering of the options.

3.8.2-MCDM and its usefulness
There are many benefits that can be achieved through implementing MCDM techniques while dealing with subjective judgement of decision makers. The following is a list of these benefits:

- Weights and scores are used to provide an audit trail.
- Weights and scores are explicit and developed according to established techniques and they can also be cross-referenced to other sources of information on relative values and amended if necessary.
- Performance measurement can be sub-contracted to experts and does not necessarily need to be left in the hands of decision-makers.
- The choice of objectives and criteria are open to analysis for any decision-making group and changes are possible when there are inappropriate options.
- It provides strong communication within a decision-making body and wider community.
- MCDM is explicit and open.

There are a number of reasons for selecting Fuzzy logic and AHP within MCDM techniques. The most appropriate technique depends on user expectation and required outcome. The following is a list of criteria which are useful for selecting Fuzzy approach AHP within MCDM techniques.

- Internal consistency and logical soundness
- Transparency
• Ease of use
• Data requirements not inconsistent with the importance of the issue being considered
• Realistic time and manpower resource requirements for the analysis process
• Ability to provide an audit trail

3.8.3-Justification for using Fuzzy Logic
Fuzzy logic is known to be a tool for MCDM problems as it proposes a rigorous framework for solving different kinds of control problems and provides a practical and inexpensive solution for complex systems. In order to deploy fuzzy logic, it is important to understand its principles and concepts and learn how it can be implemented in a decision-making problem.

Fuzzy logic was developed in the mid-1960s by Professor Lotfi Zadeh who recognized that the nature of boolean logic is not appropriate for real world problems as it considers everything to be either 0 or 1. Therefore, to address this deficiency he expounded the concept of fuzzy logic which instead of considering everything to be either completely true or false, it allowed for a degree of truth to be partially true or partially false at the same time.

There are three main steps in any fuzzy logic modelling: fuzzification, rule evaluation and defuzzification. These steps help to define a grey area instead of black and white areas.

In fact, the main reason that fuzzy logic has been selected to be implemented in the present research is its capacity to identify a grey area when there is a need to combine the views of different managers. This has already been explained for the purposes of this thesis but it is worth repeating here. When an asset manager asks all
managers to describe the most critical part of the plant, he is likely to get 6 completely different lists: the safety manager will report those components that could potentially cause a catastrophic incident and his view cannot be ignored; the production manager will report those components that could cause a downtime which directly affect loss of production; the maintenance manager will report those components with the highest failure frequency and so on. There is a need to introduce a grey area to such a decision-making process and fuzzy logic is a very useful approach to do this.

The other reason that fuzzy logic should be considered in SDMM is its ability to reduce uncertainty. For example, a safety manager used his/her subjective judgement about two machines to predict the consequences of failure and likelihood of failure. Even though both machines might have similar failure behaviour but were classified in two different levels of criticality as it is illustrated in Figure 7 The main concern is that slight changes in the qualitative judgement of experts in predicting consequences or likelihood of failure could potentially change the whole level of criticality whilst such judgements may in fact be nothing more than an expert’s guess.

This may also mean that the machine that has been allocated lower criticality might not be considered for investment even though it has the same level of priority as other machines that are given maintenance investment.
Therefore, it is essential to deal with such human error using fuzzy logic. A fuzzy approach deals with such concerns and reduces the risk of uncertainty by introducing an additional area for such machinery located between the original two.

![Figure 7](image7.png)

**Figure 7** - The possible results of expert's subjective judgement for two machineries. The red circles represent the machineries positions.

Last but not least, fuzzy logic is not only applied to compare the views of different managers but also to compare the fuzziness between four dimensions that have been...
considered as inputs to a main criticality model. These are: technical perspective, operational perspective, financial perspective and commercial perspective.

To be more specific, for those researchers that are interested in ranking all attributes the best option will be Lexicographic; those who are focusing on defining ideal and negative ideal need to apply TOPSIS; whereas those who are looking for pairwise comparisons of ideal points need to use LIMAP. Most importantly, for those researchers who are mainly focusing on pairwise comparisons of attributes and alternatives then the best MCDM method would be AHP.

3.8.4-Justification for using AHP in present research
The classification of MCDM methods could provide an opportunity for the researcher to understand what type of method might be appropriate for a specific problem. During the last couple of decades there have been many MCDM methods developed, such as AHP, Technique for Order-Preference by Similarity Ideal Solution (TOPSIS), ELimination Et Choix Traduisant la REalité which means ELimination and Choice Expressing REality (ELECTRE), etc. Accordingly, different classifications have been considered for MCDM methods. (White, 1982) proposed a hierarchical model to classify MCDM based on the availability of information in which it was updated with (Turskis and Zavadskas, 2011).

However, very little work has been carried out to classify MCDM methods based on input data, i.e. what types of information need to be considered as input. (Yang., 1998) argued for the need to classify MCDM methods based on the type of information that needs to be considered as input into the MCDM methods. A specific framework was then proposed in which MCDM methods were classified depending
on their inputs information and also whether there was a need to make pairwise comparisons between alternatives and attributes or both.

It was discussed that the most appropriate MCDM methods for decision problems that need to provide weight for criteria as inputs to the model are AHP, TOPSIS and Lexicographic. However, in order to recognise which approach is the best it is important to consider the researcher’s preferences.

To be more specific the nature of research, availability of data whether it’s weights given beforehand or relative weights will be generated, the most appropriate type of MCDM tools can selected, for instant those researchers that are interested in ranking all attributes by relative weight can use any AHP, TOPSIS, ELECTRE depending on whether weights of attributes is given beforehand or relative weights will be generated. Thoes researchers that have their data weithing beforehand can use TPOSIS or ELECTRE. However, for those researchers who need to generate weightings for attributes are mainly focusing on pairwise comparisons of attributes need to select AHP.

In other words, there are two main rules to select the best MCDM method: first, what input evaluation data is required, i.e. weight assignment, weight given beforehand, weight to be generated, etc; and second, how the researcher’s preferences are acquired and represented, i.e. comparing either attributes or alternatives, or making pairwise comparisons for both attributes or alternatives.

As far as the AHP is applied in the second phase of SDMM and it is trying to track the consequence of decision-makers’ attitudes towards maintenance strategy, it requires the decision-makers to provide the weighting for each of the attributes. This means that weighting needs to be generated and also that, as the SDMM asks
decision-makers to compare the relative importance of one alternative (i.e. maintenance strategy) with respect to other types, the best MCDM method is AHP.

In order to have a clear perspective about why AHP has been considered for the present research, the answers to the following questions have been provided according to the decision tree proposed by (Yang., 1998) for selecting a MCDM method.

- *Is preference information required?* As far as the second phase of SDMM designed to investigate the consequences of the decision made towards maintenance therefore the input data will be generated depending on the view of decision makers. Therefore, the answer to the above question would be yes. According to the structure of decision three, giving a positive response would lead to the following question.

- *How is preference information represented?* Preference information can be divided into three categories: a) utility function, b) relative weighting and c) standard level on each attribute. When the purpose of research is to track the attitudes of decision-makers by asking them to provide verbal weighting for each attributes and then quantify their subjective judgement for each attributes, therefore the SDMM requires weighing from interviews. Thus, the answer to this question would be relative weighting.

- *Is weight given beforehand or will it be generated?* This is a very important question in terms of the present study. The answer to this will be provided more comprehensively in the discussion chapter. To provide a brief answer for the current stage of research, all the weighting should be generated. This means that in order to model a culture of safety or cost-cutting within an
organisation, it is critical that all criteria and their weighing should be generated depending on the culture of asset management. In fact, the results of the sensitivity analysis could provide very useful feedback for decision-makers, and it provides an opportunity to learn from inappropriate weighing. As such, the best weighting scale can be generated over the long-term during which the decision-makers can understand the consequences of their decisions and how continues improvements can be achieved.

- **What type of input data is available?** As far as the relative importance of criteria and alternatives are both required by SDMM, this needs to be provided by decision-makers. Therefore, input data are the qualitative judgement of decision-makers for comparing attributes and alternatives. Therefore the best MCDM method is considered to be AHP because the second part of the model focus on identifying the priorities of maintenance strategies based on the pairwise comparison of the criteria.

In addition there are more advantages of using AHP for the current research in compare to other MCDM methods. These are summarised briefly here.

- **Trade-off:** It enables the decision-maker to find the optimum trade-off by considering the relative priorities factors in the best alternatives.

- **Measurement:** It proposes a method for establishing priorities as well as providing a scale for measuring intangibles.

- **Hierarchic structure:** It represents the logical tendency of the brain to arrange components of a system into different levels and to group similar elements in each level.

- **Consistency:** It tracks the logical consistency and allows cross-checking
between the different pairwise comparisons which results in consistent judgements for identifying priorities.

- **Process Repetition:** It enables a decision-maker to revise their understanding of problem. This results in improvement of their judgement through repetition.

- **Complexity:** It allows decision-makers to better focus on criteria and sub-criteria while dealing with complex problems and allocating weight to each criterion with the aid of integrated deductive systems approaches.

- **Unity:** It provides flexible, easily understood and a single model for variety of unstructured problems.

There are also some limitations and disadvantages of AHP. These are summarised in the following:

- It is limited only to problems that have a hierarchical structure or unidirectional relationship.

- Comparisons in AHP are only performed between elements at the same hierarchical level. It cannot perform in the network format. Analytic Network Process (ANP) is the MCDM technique that can deal with such a capability.

- Saaty states that ANP is a generalised form of AHP (Saaty, 2004).

An AHP model has its limitations when there is a non-trivial dependency among elements so the new structure cannot simply be processed by a standard AHP.
3.9-Conclusion

This chapter began by exploring the existing research methodologies in management science. It then discussed the researcher’s philosophical point of view for the present study. Accordingly, the strengths and weaknesses of each method were discussed briefly and the most appropriate type of research methodology for the present study was identified as one that combines qualitative and quantitative methods – the mixed approach.

The way that primary and secondary data are gathered through interviews and case study analyses was also discussed. More importantly, the reason behind using techniques such as AI and MCDM tools was highlighted and the justification for using fuzzy logic and AHP was provided among other available techniques.

In addition, it was comprehensively explained how qualitative exploration helps in the development of SDMM and consequently how it helps in the validation of usefulness of the proposed model.
CHAPTER 4: Case Study analysis

4.1-Introduction
This chapter will discuss the case studies that contributed to the development of the strategic decision-making model for selecting critical components and hence deciding on the maintenance strategy. The case studies can be categorised into two groups: the first group refers to those that enable the researcher to develop the proposed model, and the second refers to those that enable the researcher to validate the usefulness of the proposed model.

The first type of case studies was considered in the taught master classes in the maintenance and asset management courses. The analysis of such case studies investigated the existing gap between maintenance and asset management which was perceived to be the reason for lack of decision analysis. In order to deal with the lack of decision analysis, a decision-making framework for implementing condition based monitoring was proposed for an oil process plant and was then presented to experts with industrial and academic experience. Their feedback is considered which framed the modified vision of proposed model. These case studies are discussed in sections 4.2 and 4.3.

More importantly, the second types of case studies are considered to show how the proposed model can be implemented in actual practice and what benefits could be obtained from the model. In other words, the usefulness of SDMM was tested by analysing the case studies that have experiencing a catastrophic incident. It was demonstrated how SDMM contributed to learning from failures and achieving continues improvement. Even though in actual practice there are established methods to identify critical parts of assets, analysis of failure reports of recent disasters confirms that Oil & Gas industrial assets have been suffering from a lack of strategic
decision analysis. This is an issue which requires considerable attention from asset managers.

4.2-The BP oilfield case study

4.2.1-Introduction
The BP oilfield was developed between 1988 and 1990 and brought on stream in June 1990 at a cost of £500m. Eleven wells supplied oil which was piped back into a central gathering station. Due to the zero planned maintenance, the availability of the plant reached 99.93% which resulted in a dramatic increase of throughput of 150% of the initial designed capacity. Due to the availability of wells, 95,000 barrels of stabilised crude oil were produced daily as well as 16 million standard cubic feet and 670 tonnes of LPG.

The process plant was designed to process 66,000 barrels of oil every day. The design philosophy of the process plant was to install spare parts for each machine duty apart from the main refrigeration and gas compressor which makes sparing of machineries uneconomical.

The UK oilfield process plant was selected for case study analysis to investigate traditional approaches to identifying critical components that require investment. Also, the traditional approach of selecting the most appropriate candidate for implementing CBM was challenged.

During this case study analysis the application of artificial intelligence techniques and multi-criteria decision-making tools for such decision-making problems is discussed and a decision-making formwork for implementing CBM is proposed in which two criteria are considered as bases of decisions for CBM prioritizing utilizing fuzzy logic and this is followed by focused action using the Analytical Hierarchy
Process (AHP) that enables decision-makers to make pairwise comparisons between criteria. Interestingly, the model provides an opportunity to investigate appropriateness of CBM with respect to other maintenance strategy alternatives.

4.2.2-Culture of asset management
Even though the initial design philosophy of a plant was to install a standby to increase reliability of the plant, but installing a spare part for each machine duty provides an opportunity for asset managers to take advantage of system availability and in fact this is exactly what happened in this case.

Due to a small debottleneck and the extra well availability, the asset manager decided to use all spares in the main production process to increase production rate to 95,000 barrels of oil produced every day. More surprisingly, the asset management decided to install two gas turbines to burn more gas which debottleneck the plant even more and increased the production up to 99000 bpd. In fact, such a culture of asset management provides no redundancy at all for the whole asset.

As a result of such attitudes of asset managers, the following rotating equipment broke down during the first few years of plant operation:

- Small sized pumps and compressors (up to 15W) 92
- Medium sized pumps and compressors (15 to 75kW) 62
- Large pumps and compressors (above 75 kW) 37

Since operations began, the traditional maintenance practices were challenged by plant operators and zero planned maintenance was carried out for rotating equipment. The maintenance department requested the implementation of condition based monitoring for all rotating equipment to deal with some safety concerns. The maintenance department suggested that there are many ways in which the condition
of equipment should be monitored by considering a variety of approaches such as thermography, ultrasonic, vibration, electrical, visual inspection, internal inspection, lubrication and many others. However, this request was denied by asset managers.

On the other hand, asset managers argued that condition monitoring carries significant costs and it would be considered if and only if the potential cost saving exceeded the cost of monitoring. Therefore, the management team requested to identify critical rotating equipment that can provide cost benefit from CBM implementation compared to the traditional approach. There have been over 190 components of rotating machinery in which it was requested to short list the most critical rotating machinery in terms of safety, cost, and environmental consideration. Therefore a fault and criticality matrix approach was implemented to determine a cost-effective monitoring strategy.

4.2.3- Criticality Assessment Method Used in the Plant
The machine criticality assessment method used in the process plant considers five point and five grade systems for evaluation of any machine in the plant. A single criticality assessment value is produced for each machine which represents the machine’s importance to plant, and plant safety. A numerical value of this theoretical assessment method ranges from 5-25 i.e. the summed value of five grade system. The evaluation of five grad system for each machine is considered as following:

- Safety: the number 1 considered for minimal consequences and number 5 represent the potential dangerous consequences

- Operating point: represent the correlation of operating point with respect to maximum designed capability i.e. number 1 consider when the operating is
approximately around 50 present of maximum deigned rate and number 5 indicates that operation is around maximum designed rate.

- **Operational Reliability**: can be obtained both from generic or historical data which is indicator of long term reliability of unit type service. The number 1 assigned for machines with very high reliability and number 5 considered for potential unreliable machines.

- **Process Criticality**: the effect of machines lost on the overall process. The value more than 4 assigned for machines that the sparing is uneconomical due to the high capital cost. The number more than 3 considered if a drained standby is available (delayed availability). The number 2 considered if standby spare installed. And finally if unspared and low capital cost then machine considered being of low criticality i.e. number less than 2.

- **Capital cost**: represent the cost associated with mechanical failure or service deterioration obtained during overhaul.

The numerical values given for assessment are considered based on the financial evaluation i.e. the financial benefit gained through maintaining minimum required performance level, increasing plant availability and reduction of maintenance cost. Moreover it is necessary to investigate the complexity and level of appropriate condition monitoring techniques required for detecting service faults and condition monitoring. The criticality level of each machine is identified based on both practical and financial monitoring terms. The following represents the assessment value for criticality threshold.

- **Non Critical**: refers to those machines that achieved the overall criticality assessment value less than 10 where the condition monitoring is not useful
either because the data assessment do not generate useful results or it is not financially justifiable.

- **Low Criticality**: Criticality assessment value is 10-12, mostly machinery with standby categorized in this level. And there is possibility of marginal financial return.

- **Medium Criticality**: Criticality assessment value is 13-16, machinery directly operating in production process situated in this level in which spare machine usually provided. The probability of achieving financial returns is reasonable. The basic monitoring performance will provide a valuable indication of condition.

- **Critical Machinery**: Criticality assessment value is +16-25, where sparing economically impossible and financial benefit can considerably obtain through condition based maintenance.

**4.2.4-Maintenance strategy in the plant**
The initial maintenance strategy for 96 pieces of rotating equipment was to change the filter and lube oil every six months and a reactive approach was considered for 96 other pieces of rotating equipment in which none of the rotating equipment had been considered for lube oil analysis. However, after critical rotating equipment were identified, the mix approach was considered. Ninety-six pieces of rotating machinery were considered for vibration monitoring and 166 pieces of rotating machinery were considered for lube oil analysis.

One of the main reasons that oil analysis was considered for 166 pieces of machinery was the potential cost saving that such an approach provided for the asset. It was perceived that the costs associated with routine filter and oil changes every 6 months
could be dramatically reduced by oil analysis as this would inform the maintenance team when it was necessary to change the oil. More interestingly, such analysis provides information which enables maintenance teams to identify and rectify any problems before they cause damage.

4.2.5-Critical commentary
There are some important concerns about such criticality assessment methods. The main concern is that slight changes in the qualitative judgement of experts when predicting the numerical values of each criterion could potentially change the whole level of criticality. At the same time, such judgements might be nothing more than an expert’s best guess. This means that a machine that has been allocated a low criticality might not be considered for investment.

One could argue that it is very probable that different operators provide different values for different criteria for which different outcomes of criticality would be obtained; in fact, it is very difficult for maintenance staff or experts to provide correct numerical evaluation (Braglia et al., 2003). In other words, the values provided by operating and maintenance technicians are qualitative judgement. Therefore, such an approach appears to be less precise and the following model has been developed to improve such decision making problems.

4.2.6-Developing a model for CBM implementation
As discussed in previous chapters, different approaches have been available to address such decision making problems. One of the best-known approaches to deal with such concerns can be considered as implementation of fuzzy logic (Sharma et al., 2005b, Kutlu and Ekmekcioğlu, 2012) but this is not as effective as combining artificial intelligence techniques and multi-criteria decision-making tools. In fact AHP enables decision-makers to make pairwise comparisons between criteria.
As far as fuzzy logic cannot deal with consistency of subjective judgments therefore it combined with AHP in which it can be used to overcome such shortcomings of fuzzy logic.

### 4.2.6.1-Developed model: Phase one

Allocating a maintenance budget to improve safety and availability has always been a controversial topic in industrial plant because many asset managers have argued that it is important to find the most appropriate trade-off to get the best out of the investment.

There have been many academic attempts to find the most appropriate trade-off between cost and other criteria. For instance, (Tsoi et al., 1995) proposed an algorithm to evaluate cost and environmental impact; (Hackney and De Neufville, 2001) proposed a model to determine cost, emissions and energy trade-offs; and (Martínez et al., 2005) suggested a hierarchical linguistic model to consider optimum cost and safety concerns for engineering design.

The author developed a model to address the problem raised in the case study analysis. As far as the main concern of asset management was to find the most appropriate trade-off between cost and safety, the model developed initially to address such issues.

In fact, the first stage of the model demonstrates how the criticality of equipment could be determined in terms of safety and cost concerns where the effectiveness of fuzzy logic has been presented.

In order to understand how AI applied to such a decision-making problem, the three steps of defining the problem for fuzzy logic will be set out next. A more in-depth
assessment will be provided in the next chapter to show how fuzzy logic needs to be applied to decision-making problems when discussing the SDMM.

In order to create any decision problem, there are three steps that must be defined in the fuzzy logic Matlab toolbox:

(i) Fuzzification

(ii) Rule evaluation

(iii) Defuzzification

4.2.6.1.1 - Fuzzification
The first step in defining a decision problem in fuzzy logic is known as fuzzification where it is necessary to define inputs that need to be taken into account as the basis of decision-making. In this case study analysis, two criteria, cost and safety, are selected as inputs to the decision-making framework. Figure 9 shows the structure of the decision model in fuzzy logic.

![Figure 9 - Cost and Safety as input to fuzzy model](image)

Five membership functions are defined for each criterion. The first input considered is the cost associated with maintenance, ranging from 0 to 100 units of cost. Consequently, values from 0-20 units of cost are considered as Very Low
Membership Functions (M.F), values from 10-40 are considered as low M.F, values from 30-60 are considered as Medium M.F, values from 50-80 are considered as high M.F, and values from 70-100 are considered as very high M.F. Figure 10 shows the range of each membership function in terms of cost.

![Membership function plots](image1)

Figure 10-Cost membership functions in fuzzification phase

The second input considered is safety. Five membership functions are defined to illustrate the level of safety, varying from minimal to very high consequence. Figure 11 represents how the level of safety varies from minimal consequences to very high consequences from item shutdown to excavations. As can be seen in Figure 11, the numerical values for safety are defined between 0 and 1.

![Membership function plots](image2)

Figure 11-Safety Membership functions in Fuzzification Phase
4.2.6.1.2-Rule evaluation and defuzzification
When the sets of membership functions are defined for each criteria, the modelling can then proceed to the next stage, i.e. the rule evaluation stage where specific rules will be allocated for each possible combination of membership functions. The rules are generated as per Table-1. For instance, if the cost associated with maintaining a piece of equipment are considered to be very low and if there are minimal or no consequences associated with it failing during operation then it is considered to be non-critical.

Table 1-Cost versus safety matrix which indicates the rules in rule evaluation phase

<table>
<thead>
<tr>
<th>Safety Vs Cost</th>
<th>No Consequences</th>
<th>Item Shutdown</th>
<th>Unit Shutdown</th>
<th>Plant Shutdown</th>
<th>Evacuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Low cost</td>
<td>Non Critical</td>
<td>Non Critical</td>
<td>Medium Critical</td>
<td>Medium Critical</td>
<td>Critical</td>
</tr>
<tr>
<td>Low Cost</td>
<td>Non critical</td>
<td>Low Critical</td>
<td>Medium Critical</td>
<td>Medium Critical</td>
<td>Critical</td>
</tr>
<tr>
<td>Medium Cost</td>
<td>Low Critical</td>
<td>Low Critical</td>
<td>Medium Critical</td>
<td>Critical</td>
<td>Critical</td>
</tr>
<tr>
<td>High Cost</td>
<td>Medium Critical</td>
<td>Medium Critical</td>
<td>Critical</td>
<td>Critical</td>
<td>Highly Critical</td>
</tr>
<tr>
<td>Very high cost</td>
<td>Medium Critical</td>
<td>Medium Critical</td>
<td>Critical</td>
<td>Highly Critical</td>
<td>Highly Critical</td>
</tr>
</tbody>
</table>

The defuzzification step allocates criticality according to the rule evaluation step. For instance, IF a component has high consequences in term of safety which leads to plant shutdown AND the associated cost related to mechanical failure and its maintenance is high THEN the defuzzification for this combination determines the component to be critical for investment. Figure 12 and Table 2 illustrate this.

Figure 12-The defuzzification membership function for CMP implementation
<table>
<thead>
<tr>
<th>Rule Number</th>
<th>If Unite of Cost is</th>
<th>And Safety is with</th>
<th>Then Criticality Level is</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very Low</td>
<td>No Consequences</td>
<td>Non Critical</td>
</tr>
<tr>
<td>2</td>
<td>Very Low</td>
<td>Item Shutdown</td>
<td>Non Critical</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>No Consequences</td>
<td>Non Critical</td>
</tr>
<tr>
<td>4</td>
<td>Medium</td>
<td>No Consequences</td>
<td>Low Critical</td>
</tr>
<tr>
<td>5</td>
<td>Low</td>
<td>Item Shutdown</td>
<td>Low Critical</td>
</tr>
<tr>
<td>6</td>
<td>Low Critical</td>
<td>Item Shutdown</td>
<td>Low Critical</td>
</tr>
<tr>
<td>7</td>
<td>Very Low</td>
<td>Unit Shutdown</td>
<td>Medium Critical</td>
</tr>
<tr>
<td>8</td>
<td>Low</td>
<td>Unit Shutdown</td>
<td>Medium Critical</td>
</tr>
<tr>
<td>9</td>
<td>Medium</td>
<td>Unit Shutdown</td>
<td>Medium Critical</td>
</tr>
<tr>
<td>10</td>
<td>Very Low</td>
<td>Plant Shutdown</td>
<td>Medium Critical</td>
</tr>
<tr>
<td>11</td>
<td>Low</td>
<td>Plant Shutdown</td>
<td>Medium Critical</td>
</tr>
<tr>
<td>12</td>
<td>High</td>
<td>No Consequences</td>
<td>Medium Critical</td>
</tr>
<tr>
<td>13</td>
<td>High</td>
<td>Item Shutdown</td>
<td>Medium Critical</td>
</tr>
<tr>
<td>14</td>
<td>Very High</td>
<td>No Consequences</td>
<td>Medium Critical</td>
</tr>
<tr>
<td>15</td>
<td>Very high</td>
<td>Item Shutdown</td>
<td>Medium Critical</td>
</tr>
<tr>
<td>16</td>
<td>High</td>
<td>Unit Shutdown</td>
<td>Critical</td>
</tr>
<tr>
<td>17</td>
<td>High</td>
<td>Plant Shutdown</td>
<td>Critical</td>
</tr>
<tr>
<td>18</td>
<td>Medium</td>
<td>Plant Shutdown</td>
<td>Critical</td>
</tr>
<tr>
<td>19</td>
<td>Medium</td>
<td>Evacuation</td>
<td>Critical</td>
</tr>
<tr>
<td>20</td>
<td>Very High</td>
<td>Unit Shutdown</td>
<td>Critical</td>
</tr>
<tr>
<td>21</td>
<td>Low</td>
<td>Evacuation</td>
<td>Critical</td>
</tr>
<tr>
<td>22</td>
<td>Very Low</td>
<td>Evacuation</td>
<td>Critical</td>
</tr>
<tr>
<td>23</td>
<td>Very High</td>
<td>Plant Shutdown</td>
<td>Highly Critical</td>
</tr>
<tr>
<td>24</td>
<td>High</td>
<td>Evacuation</td>
<td>Highly Critical</td>
</tr>
<tr>
<td>25</td>
<td>Very High</td>
<td>Evacuation</td>
<td>Highly Critical</td>
</tr>
</tbody>
</table>
4.2.6.1.3- Fuzzy Surface Results
One of the advantages of fuzzy logic is its ability to create visual results that can be understood by asset managers who do not have an engineering background. Once the decision-making problem is defined for fuzzy logic, it provides decision surface results depending on how M.F and the rules are defined to structure the problem for fuzzy logic. Figure-13 demonstrates the surface results obtained from modelling the problem in the case study. In fact, by providing such visual figures the decision-maker can track the criticality of equipment in the asset while comparing two criteria: cost and safety.

![Fuzzy logic surface results for identifying criticality level of each equipment in asset](image_url)
4.2.6.2-Developed model: Phase two
The second stage of the model is called focused action which allows experts to investigate a maintenance problem from their own perspective and optimize their final decision. The second phase of the model aims to demonstrate how AHP can be applied for decision-making in maintenance strategies; for this case study, the main concern of asset management was to implement CBM.

Once the critical equipment has been recognized in terms of cost and safety, the focus action can be put in place by applying multi-criteria decision-making tools. AHP was proposed by (Saaty, 1990) who discussed how AHP can be implemented in a decision-making problem. The concept of AHP is comprehensively discussed in the next chapter but a brief introduction will be given here. AHP represents the logical tendency of the brain to structure a decision problem in a hierarchical structure where the top of the hierarchy is identified as the goal. In this research, the goal is to select the most appropriate maintenance strategy, and the objectives to achieve the goal define in mid-level of the hierarchy. Finally, the possible alternative actions defines at the last level of the hierarchy, i.e. different maintenance strategies.

![Hierarchical structure of selecting the most appropriate maintenance strategy](image)

<table>
<thead>
<tr>
<th>RTF</th>
<th>FTM</th>
<th>CBM</th>
<th>DOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run To Failure</td>
<td>Fixed Time Maintenance</td>
<td>Condition Based Monitoring</td>
<td>Design out Maintenance</td>
</tr>
</tbody>
</table>

Figure 14-Hierarchical structure of selecting the most appropriate maintenance strategy
AHP provides an opportunity to make pairwise comparisons between criteria to obtain the appropriate alternative in consideration of the relative importance of one factor with respect to other factors. Figure-15 presents how AHP applies to the current case study.

One of the important features of AHP is that it can track the consistency of a judgement made for a pairwise comparison between criteria. In other words, it assesses the accuracy of judgments made by decision-makers. Figure-16 illustrates how the relative importance of one criterion has been taken into account with respect to other criteria. It provides a consistency ratio of 0.07 which is less than 0.1. This means that those judgements were consistent and there was no need for a re-judgement.

As it can be seen in Figure-16, for each machine that has been identified as being critical there are 5 criteria that will be compared with respect to each other. The criteria have been selected according to the criteria presented in the case study, and this is used as the basis of the decision for selecting CBM techniques.
As illustrated in Figure-16 more emphasis has been placed on reliability instead of cost, and similarly, more emphasis has been placed on safety instead of reliability and so on. In fact, the proposed AHP model established a framework for professionals who are keen on making pairwise comparisons between criteria whilst making decisions on implementing maintenance strategy.

It is important to mention that the AHP model is developed based on the data available in the case study and can be adapted for any other industrial plants. In other words, the proposed model presents the application of AHP for such decision-making problems and it can be modified according to the knowledge and experience of experts in any industrial plant.

2.4.7-Simulating BP oil process plant using Fuzzy AHP approach

In order to elaborate in more detail how the proposed Fuzzy AHP approach can be implemented in this case study, more data are required. However, as discussed in the research methodology chapter, one of the main drawbacks of the case study approach can be the limitation of data in the case studies. Therefore, in order to deal
with such a limitation it was decided make some assumptions to present how such a fuzzy AHP approach can be implemented in this case study.

The following present the application of fuzzy logic to identify critical equipment for this case study. Assume after extracting data from CMMS packages and/or historic failure database, the criticality of machine A, B, C, D, E, F, G has been identified as presented in Figure-17.

![Figure 17](image-url)

**Figure 17-The criticality levels of equipment in the plant in terms of cost and safety**

Let us imagine the unit cost for Machine A is derived from CMMS packages and its failure consequence has been identified as the plant shutdown. Therefore, by drawing a perpendicular line to the cross-section lines of cost and safety with values of 80 and 0.8, the criticality level of machine A can be perceived as more than any other machine. Machine A can refer to an expensive gas turbine for which installing a spare is not economical and its failure can cause an immediate result in the
production loss that might cost millions of pounds per day. More importantly, its failure could potentially cause a plant shutdown and in the worst case scenario it might result in plant excavation.

Any other machines within the asset that might display similar behaviour to Machine A need to be considered as highly critical for maintenance investment and need to be considered for focused action, i.e. AHP implementation. Figure-18 presents the results obtained from AHP for machine A.

![Figure 18-Sensitivity analysis results obtained from AHP, it provides the relative importance of one criterion with respect to others in terms of different alternatives.](image)

As can be seen in Figure-18, whilst the judgement has been taken into account to rate the relative importance of one criteria with respect to others for Machine A, safety has been marked as the most important criteria. The second most important criterion is the importance of the machine for the process. Machine A directly affects the production rate and as far as it has no redundancy the importance of its reliability can be put in third position. It is important to state that for such a critical component no
one would consider the maintenance cost. Any asset manager would invest in such a machine without hesitation, and this is the reason why the importance of cost criteria is placed in fourth position. Figure-19 presents the dynamic sensitivity of nodes in which the relative importance of criteria and alternatives have been identified for Machine A.

Figure-19 shows that the best maintenance alternative is CBM. As discussed earlier, the main challenge of the BP case study was to identify the critical equipment that are most appropriate for investing in CBM. In fact, AHP implementation not only helps to identify the best maintenance strategy but also prioritises the best maintenance alternatives after CBM implementation. After CBM, for Machine A the best alternative is DOM, FTM and reactive maintenance respectively. For example, once CBM has been considered for the gas turbine and it runs for a many years of operation, the next candidate for maintenance alternative cannot be considered as fixed time maintenance. Rather, the design out maintenance will be recommended by
the AHP model where the new generation of gas turbines would provide the most advantages for the plant.

It could be argued that it is very easy to make a decision that investing in CBM techniques is essential for such a gas turbine and therefore it is unnecessary to consider such an AHP model for other machines with the same criticality. This issue is considered in the discussion chapter when analysis is carried out of the results obtained from SDMM. However, in order to briefly explain such a concern the results obtained for Machine B will now be discussed.

Figure 20-Sensitivity analysis results obtained from AHP for Machine “B”

In order to do this, it is useful to compare the criticality level of machines A, B, C and E as illustrated in Figure-17 and then discuss the results obtained from Figure-18 and Figure-20.

It is important to note that comparing cost and safety and finding the trade-off is one of the most challenging aspects of managing an industrial plant. Here in the case study analysis, cost and safety have been compared to each other because it was part
of the culture of asset management during the operation of plant in the 1990s. The next chapter will discuss how SDMM dealt with the comparison of such criteria as in recent years such comparisons have been argued to be illegal. Before comparing the criticality level of different machines in Figure-17, it is important to note that the proposed fuzzy model compares a quantitative factor i.e. cost with safety factor which is obtained from both qualitative and quantitative values i.e. likelihood of failures which are quantitative and consequence of failures which are almost qualitative. This means that slight changes to qualitative judgements obtained could change the level of criticality from high to medium and so one. The position of Machine B to Machine E can change and so too Machine C to Machine E depending on the results of different qualitative judgements. In fact, the whole level of criticality for each machine can change simply because of subjective judgments of decision-makers. In actual practice, there are many items that are located on the borders of different criticality levels which require specific attention. This is the reason why the fuzzy AHP approach has been considered as fuzzy deal with uncertainties of judgement and AHP deal with consistency of subjective judgements made by decision-makers.

To answer briefly the above criticisms, it can be argued that in such industrial plants there are techniques such as quantitative risk assessments (QRA) which identify the most critical part of assets, similar to the criticality assessment method explained in this case study. One of the most challenging parts of such QRA assessments is that they provide a long list of equipment that have a low likelihood of failure with high consequence impact. Techniques such as QRA argue that there are many items that are critical and in fact a long list of equipment for maintenance investment discourages asset managers for appropriate investment on maintenance strategy.
Therefore, such a fuzzy AHP approach can be used to reduce the number of items that are necessary for maintenance investment.

As illustrated in Figure-18 and Figure-20, the maintenance strategy proposed by AHP for Machine A and B can be compared as the priority of the maintenance strategy varies for Machine B because the best alternative is CBM followed by FTM rather than DOM.

2.4.8-The contribution of fuzzy AHP approach to case study
Figure-21 summerizes the process of maintenance strategy in the case study where the contribution of proposed model has been highlighted with red lines.
4.3-Oil and gas production platform investigation

4.3.1- Purpose of investigation
The current maintenance and criticality practice of a specific oil and gas production platform in the North Sea has been investigated in order to understand the need for the strategic development of the decision-making model to select critical components and hence maintenance strategy in the platform which has annual output of 15 million barrels of oil and 18 million standard cubic feet of natural gas.

This case study is based on questions that were asked of a maintenance department for a North Sea oil production platform on how to improve the performance of the asset.

• What is your vision for maintenance?
• What objectives will you set to ensure that you move towards your vision?
• What key performance indicators will you monitor to ensure that you are on track?

![Figure 22-- The hierarchical view of setting vision for maintenance management](image)

It was then requested that answers for each of the questions on vision, objectives and key performance indicators should be linked together in the most consistent way.
4.3.2- Criticality assessment practice for oil production platform

Unlike the previous case study where the asset manager asked the maintenance department to determine the most critical part of the process plant, in this case study the list of systems were provided in which it was requested to find out the most important components while answering to pre-defined questions. Therefore, the process used to review criticality and then the maintenance task was based on providing some numerical values for each question. The first stage of review was to evaluate the criticality of the following systems:

- Wellhead
- Production Separation
- Oil Metering
- Gas Dehydration
- LP Compressor 1st Stage
- IP Compressor
- HP Compressor
- Gas Metering
- Produced Water Treatment
- Water Injection
- Seawater Lift
- Oil Export
- Misc. Permanent Equipment/GBS
- Fresh Water
- Process Drains
- Flare
- Fuel Gas
- Aviation Fuel
- Firewater
- Safety Equipment
- Compressed Air
- Chemical Injection
- Mechanical Handling
- Main Power Generation
- Emergency Power Generation
- HVAC
The criticality of the above system then assessed by assigning numerical values for the following factors, it starts with asking the questions like what functional failure of this item result in? And the proving ranking for the following concerns.

1. Harm to people
2. A reportable environment incident
3. Production Loss
4. Dose item have a installed spare
5. Failure of spare causes production loss
6. Item or spare failure increase fixed operational maintenance repair cost more than £20000?
7. Plant operational integrity loss
8. Probability of item failure
9. Is item/unit a safety device
10. Personnel Safety equipment exist?
11. Is it a fabric or platform infrastructure item?
12. Is it miscellaneous/general equipment?

Whilst assessing the criticality of such systems all operation and maintenance personnel get involved in the decision-making process to ensure their detailed knowledge and experiences have been taken into account. Similar to the previous case study, once the numerical assessment was complete, the top 10% of the critical components were selected for reliability centred maintenance analysis including items such as emergency power generation, main power generation and safety equipment. Accordingly, maintenance strategies for those less critical systems were decided with reference to best current practice within the oil company.
4.3.3-Developing a maintenance scorecard
The concept of a maintenance score card has been discussed in detail by (Mather, 2005b) when he describes how an oil & gas company went about developing a maintenance score card for one of its offshore production platforms. The maintenance score card can also be useful for finding the most appropriate answers to questions about vision, objectives and KPI.

In order to establish a score card, it is necessary to create a discussion group that comprises maintenance department and operations staff to identify what expectations they have about maintenance. The conclusion of such discussion groups provides the best vision for the production platform. The following are the results obtained for this case study.

4.3.4-Platform Vision
Staff working on maintenance and operations agreed to the following vision for the oil production platform:

To have a first-class maintenance and inspection programme; To be regarded as leaders in up-time and cost management. To be recognized by the regulatory bodies for outstanding maintenance and inspection management.

4.3.5-Three first level of maintenance objectives
Once the vision is identified, the objectives used to achieve such a vision are set out:

1. Inspection and maintenance activities are effective in achieving the plant performance required to achieve the business requirements.

2. Inspection and maintenance processes are effective in achieving production and integrity related objectives at the lowest cost.

3. Appropriate maintenance and inspection effort is directed towards those failures which would present a risk to asset integrity or personal safety.
4.3.6- Three maintenance key performance indicators
After the objectives were defined for the production platform, three maintenance key performance indicators were then proposed by maintenance staff which would allow the achievement of those objectives to be tracked accordingly.

- Availability
- Maintenance cost per barrel
- Compliance to plan

4.3.7- Critical commentary
As maintained earlier, there have been many different criticality assessments used in different industrial plants. There is a common limitation among these case studies; that is the way subjective judgement of experts will be taken into account for each criticality assessment method, in this particular case study similar concern highlighted by assigning values for each answer.

Even though a candle in the dark is better than nothing, one could argue that there have been many uncertainties in identifying the most critical part of the plant using subjective judgement because many assessment methods simply relied on these judgements of experts which could be guess at best.

In fact such limitations highlighted the need for combining subjective judgement of decision maker with objective values. Using techniques such as artificial intelligence during decision analysis can reduce the degree of uncertainty whilst combining the views of different experts during selection of critical equipment.

4.4- Shell case study
4.4.1-The purpose of case study
The purpose of this case study is to investigate how Shell adapted maintenance strategies for specific rotating equipment in one of its refineries which was built more than 30 years ago. In fact, within this refinery there are some pumps which are
more than 30 years old and the mean time between failures has decreased to around 2 years. This means that almost every 2 years these pumps used to fail which is the average rate in this industry. The purpose of this case study is to analyse what approach Shell has considered in order to improve reliability and availability of these pumps.

4.4.2-Selecting critical pumps in terms of production
The refinery includes 300 pumps. The maintenance department were asked to improve the reliability of these pumps. The mechanical supervisor decided to consider MTBF as a measure of reliability and made a request to the production managers to provide a list of the most critical pumps.

The production team provided a list which included almost all the pumps and then the supervisors requested the list of top 30 pumps therefore the production team assess the criticality of pumps based on their historic failure data and reported back the top 30 pumps that had the worst MTBF in their history. The mechanical supervisor decided to implement condition based monitoring for the top 30 pumps for which a portable vibration monitoring instrument was purchased with analysis software.

4.4.3-Maintenance strategy implementation
The condition monitoring techniques were taken into account for the top 30 critical pumps and they were monitored every 6 weeks. The monitoring techniques were also carried out for any other pumps that were reported as having specific issues.

The results obtained with a portable vibration monitoring device were recorded in specialist software as well as any other maintenance activity and information stored in CMMS packages in the plant.
Over the course of 7 years, a quarterly review was carried out by operators and technicians. In each quarterly meeting, a list of top 10 pumps with problems was produced and root cause analysis was considered for the top 2 problems. Procedures and methods were also changed as appropriate.

4.4.4- The Improvement of MTBF Results
As discussed previously, Shell considered only MTBF to decide on its maintenance strategy, i.e. CBM implementation. Even though identifying the critical components from a production perspective might seem to be necessary but is generally not enough to address the problem, in this case study an outstanding result has been obtained when comparing the achievement of Shell with other companies. Figure-23 shows how considering such a straightforward strategy could improve the reliability of pumps over the past 7 years in which the average pump MTBF was improved from 2 years to 10 years. In fact, the performance of pumps at Shell has been improved from an average 2 year to the best practice that is 10 years. As illustrated in Figure-23.

![Figure 23](image-url)

*Figure 23-Presents the best performance achieved by Shell to increase MTBF on 300 pumps*
4.4.5-Critical Commentary
The main purpose of using this case study was to highlight the importance of making decision based on objective values rather than subjective judgement. Even though Shell used only one criterion to identify the most critical pumps with respect to mean time between failure (MTBF) as it is the greatest concern of the production managers. Shell managed to achieve best practice by increasing the MTBF from 2 years to 10 years. In fact Shell could have achieved much greater performance if other criteria had been taken into account. These criteria could include MTTR, Importance of machine with respect to Reliability block diagram, the pattern of failure (i.e. Weibull analysis), the impact of such pumps failure on production loss and maintenance cost.

The results would have been even better if other criteria had been taken into account during criticality assessment method. In other words, reflecting only the production concerns in such decision-making could improve the availability but might not adequately address safety, reliability and many other concerns.

4.5-BP Texas City Disaster
4.5.1-Background of disaster
One of the worst industrial disasters in the history of the US is considered to be the BP Texas City disaster. The explosion of the refinery injured 180 people and killed 15. Financial losses were reported to be more than $1.5 billion. The incident was believed to have occurred during the start-up of a process unit, i.e. isomerisation (ISOM). First, a raffinate splitter tower overfilled which opened the pressure relief devices. Consequently, flammable liquids emerged from the blowdown stack and its flare system did not function. Therefore, these flammable liquids were released into the environment and found an ignition source which caused the explosion. This is
said to have occurred due to a lack of safety, a cost-cutting culture, process safety metric, regulatory oversight and human factors (CSB, 2007).

In discussing the culture of maintenance and asset management, it is worth mentioning that the Texas City refinery used to be operated by Amoco. In 1999 when BP merged with Amoco, the operation of the plant was taken over by BP.

Before investigating the causes of the incident, it is important to understand the nature of process which resulted in the explosion. Section 4.5.2 will discuss the sequence of events in more detail.

4.5.2-Incident and sequence of events
Everything began during the start-up of an ISOM unit when the raffinate splitter tower was restarted after a maintenance outage. The operation personnel overfilled the distillation which was not supposed to be done according to the start-up procedure. Figure-24 shows the main part of the ISOM unit which contributed to the explosion.

![Figure 24-Illustration of ISOM unit in BP Texas City disaster (Labib, 2014)](image-url)
Whilst flammable liquid was exceeding its maximum limit in the 53m tall distillation columns, the high level alarm failed to function. Also, the sight glass was full of dirt and so the level of liquid was not observable. The red circles in Figure-24 show the position of the high level alarms and sight glass on the tower.

The operators overfilled the tower in which the mixture of gas and liquids flowed out into the overhead pipe at the top of the tower as illustrated in Figure-25. Consequently, the emergency overflow pipe ran down the side of the tower to the pressure relief valves, see Figure-26. As the pressure in the valves increased rapidly from 22 psi to 64 psi, the liquid was discharged through the relief valves that were opened for six minutes. Therefore, a huge amount of flammable liquid moved towards the blowdown drum that had a vent stack open to the atmosphere.

Figure 25- Illustration of the fluid level with respect to time (CSB, 2007)
One of the most critical systems that contributed into the disaster considered as refinery’s blowdown system which was originally installed in the 1950s. The maintenance department was requested a design out maintenance strategy for the blowdown drum. The maintenance manager argued that there is need for new generation of blowdown drum and requested that such system need to be connected to the flare system for safe operation. Unfortunately, the unsafely-designed blowdown drum used in the ISOM unit had never been connected to a flare system. Therefore, it was unable to combust flammable vapours and contained liquids released from the process. In fact, once the flammable liquid reached the blowdown drum and stack, it overfilled and consequently a geyser emerged from the 34m tall stacks. Such a huge amount of volatile liquid evaporated whilst it was falling to the ground. It found an ignition source 7.6m away from the blowdown drum and this caused the explosion. Figure-27 shows how the flammable liquid was released into the environment.
4.5.3-Failure model and effective analysis of the event
As discussed earlier, one of the best-known techniques to identify the root cause of an incident is FMEA. This type of analysis focuses on technical problems associated with machinery within the plant.

Table 4.3 discussed how the failure of those instruments that are associated with the blowdown drum and the raffinate splitter tower contributed to the BP Texas City disaster.
However, by analysing the available investigation reports for such disasters, one can argue that there are fundamental reasons behind such technical failures which are associated with organisation behaviour and attitudes towards asset management.

4.5.4- Key organisational issues

There have been many technical and organisational issues reported for BP Texas City disaster (Khan and Amyotte, 2007, Le Coze, 2008, Manca and Brambilla, 2012, Holmstrom et al., 2006). The technical issues have been presented in previous sections. This section focuses on organisational and asset management issues that have been identified in case study analysis.

<table>
<thead>
<tr>
<th>Tag No.</th>
<th>Instrument Description</th>
<th>Function</th>
<th>Failure Mode</th>
<th>Likely Failure Cause</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT-5100</td>
<td>Raffinate Splitter Level Transmitter</td>
<td>Transmits a signal to the control system to indicate the level in the tower.</td>
<td>Incorrect reading prior to the incident</td>
<td>Instrument not calibrated for actual specific gravity of the ISOM process fluid, at operating temperatures.</td>
<td>Transmitter falsely showed the level in the tower bottoms below 100% and failing, when in fact the tower was overfilling.</td>
</tr>
<tr>
<td>LSH-5102</td>
<td>Raffinate Splitter Redundant (Hard-wired) High Level Alarm</td>
<td>Alarms when the level in the tower exceeds a maximum set value.</td>
<td>Failed to signal when the tower bottom level reached the assigned set-point.</td>
<td>Worn, misaligned components bound the mechanism.</td>
<td>Operators received no independent warning that the maximum bottom level had been exceeded.</td>
</tr>
<tr>
<td>LG-1002 A/B</td>
<td>Raffinate Splitter Sight Glass</td>
<td>Visually indicates tower level (level indication split across two sight glasses).</td>
<td>Sight glasses were dirty on the inside; tower level could not be visually determined.</td>
<td>Sight glass not cleaned.</td>
<td>Level transmitter calibration could not be effectively performed without sight glass verification. Operators had no backup to determine tower level.</td>
</tr>
<tr>
<td>LSH-5020</td>
<td>ISOM Blowdown Drum High Level Alarm</td>
<td>Alarms when the level in the blowdown drum exceeds a set value. This was the only high level alarm for the blowdown drum.</td>
<td>Failed to signal when the tower bottom level reached the assigned set-point.</td>
<td>Damaged level displacer (“float”)</td>
<td>No warning that the blowdown drum level was above maximum.</td>
</tr>
<tr>
<td>PCV-5002</td>
<td>3-b Pressure Vent Valve for the Raffinate Splitter Reflux Drum</td>
<td>Available for operators to manually vent gases from the splitter overhead system.</td>
<td>Valve failed to open during startup testing.</td>
<td>Possible actuator stem binding, or intermittent pneumatic failure.</td>
<td>Unit was started up with a known malfunction of this pressure control valve.</td>
</tr>
</tbody>
</table>
The first and most important organisational issue was reported as the cost-cutting policy which originated with BP executive managers who failed to invest in the physical asset and refused the requests of the maintenance department. Instead, they increased the pressure on the production rate which reduced the safety process during operation.

Moreover, effective oversight of the safety culture had not been provided by the BP Board of Directors who had not assigned a member of the Board to be responsible for verifying and assessing the performance of assets with respect to safety. Instead, the safety evaluation of the asset relied on parameters such as low personal injury rate which was absolutely irrelevant and failed to address real safety performance. Also, the main objective and rewards were focused on improving the safety of personnel rather than increasing the safety of the production process. BP also suffered from a lack of learning and reporting culture which discouraged the reporting of safety concerns and near misses accurately because of the blame culture originating from top level managers.

Similarly, the inaccurate reports obtained during risk assessment and the results obtained from risk management analysis vary from one to another depending on what subjective judgment has been considered for the analysis. These differences in analysis and the concern about receiving endless criticism from managers who received reports on crossing the red lines highlighted a very dangerous phenomena. Good-looking reports and analysis might make the managers happy but does not reflect the real situation. This was the case for many years of operations at BP Texas City refinery; such organisational attitudes contributed very effectively to the main catastrophe.
Last but not least, many audits, surveys and studies reported deep-seated safety problems at the refinery. However, the response of managers at all levels was “too little, too late”. In other words, different departments within the organization used to speak with different languages and such attitudes damaged the performance of the whole asset.

4.5.5-Critical Commentary & SDMM

Many organisations have made mistakes when identifying the causes of disasters. Usually, all attention is directed at the operator who pulls the wrong switch and misses the signals, and/or an engineer who miscalculates an analysis, and/or a supervisor who does not make the right decisions or does not listen to his managers. However, the organisational and asset management culture as well as human factors can play an essential role in preventing disasters.

In fact, there is a link between technical reasons for failures and organisational behaviour towards asset management. To be more specific, the failure of investment in the Texas refinery by Amoco in 1990 and the culture of cost-cutting by BP managers who targeted a reduction of 25% of the budget in 1999 and another 25% in 2005 not only resulted in a reduction in staffing, training and operators but also in the refinery’s process equipment and infrastructure falling into disrepair.

It is important to note that there had been a previous incident just a few weeks before the main BP Texas City disaster which could have been considered as a warning to asset managers not to ignore safety concerns. In early March 2005 there was a serious fire which caused a fatal accident, and also in February 2005, during the inventory of the splitter, there was a leak of hydrocarbons into the site sewer.
There have been many other deficiencies in the operation of the refinery, for instance, the mechanical integrity programmes in the asset recommended a “run to failure” approach for some of the process equipment when in fact other types of maintenance strategy should have been implemented. In addition, the overall process of safety culture was focused on some indicators that did not reflect the real problem of safety within the plant. The most attention was focused on the injury rate over the past decades. In fact, analysing different criteria and selecting wrong indicators led to the misguided and potentially disastrous belief that the corresponding criteria had been taken into account and the associated problems had been solved.

As discussed earlier (CSB, 2007), the reported organisational behaviour of BP at all levels contributed to the main disaster, and it was argued that the warning signs of such a disaster had been present in the refinery several years before the incident.

In fact, the existence of such disasters in the history of the oil refinery plant can be considered as evidence of a lack of decision analysis at different levels of maintenance and asset management. Similar to many industrial plants, many decisions are made without tracking the consequences of the decisions. In the case of BP Texas City disaster, if the BP executive managers had been aware of the consequences of their decisions for cutting-costs, they would never have made such a decision.

Many investigation reports for this case study failed to report the lack of strategic decision-making model or packages that enable asset managers to track the consequences of decisions visibility whilst considering cost-cutting culture for assets. The next chapter will extend a strategic decision-making model (SDMM) which enables the asset manager to track the consequences of decisions in the

128
maintenance department. In which the culture of cost cutting and culture of safety in the first priority has been dealt with through proposing the SDMM.

4.6-Conclusion
This chapter focused on case studies and their relevant reports which provided the process of decision-making for implementing a maintenance strategy. As discussed earlier, case study analysis is an effective approach for deepening the understanding of concepts. However, availability of relevant data was one of the main challenges during case study analysis.

The analysis of such case studies highlights the gaps in decision analysis for maintenance and asset management. This has led to the development of the strategic decision-making model (SDMM) for selecting critical components and hence selecting critical parts of plants which will be discussed in the next chapter.

There have been two types of case studies used in this chapter. The first type investigated the existing gap in the actual practice of maintenance and asset management where a framework for implementing condition based monitoring was proposed. The second type investigated the disasters in the history of oil and gas, and the current gaps in decision analysis which resulted in such disasters have been discussed. It is important to note that such case studies have been considered to validate the usefulness of SDMM while demonstrating how SDMM works in actual practice.
CHAPTER 5: Strategic Decision Making Model

5.1-Introduction:
Selecting a maintenance strategy is a multi-criteria decision-making problem which may vary from one plant to another because one asset might require putting safety in top priority, such as a nuclear plant, while another asset, such as an oil production platform, may not only need to consider safety as high priority but also need to deal with concerns such as oil prices which could even decrease to more than half of its original price (Bowler, 2015). Therefore different industries might require different approaches while making decision for maintenance strategy.

Many industrial plants have used CMMS packages to deal with decision analysis. However, much evidence has been presented in literature that suggests such packages are suffering from a lack of decision analysis (Labib, 2004). Having said that, CMMS packages have offered some benefits, such as cost management, scheduling, resource control, reduction of breakdowns and integration (Zhang et al., 2006).

Historically in maintenance management, the decision-making model was designed to optimize a single criterion, such as minimizing total maintenance cost or maximizing component availability. However, in practice there are normally many issues which need to be addressed simultaneously (Tsang, 1995).

Developing a decision-making model for implementing a maintenance strategy has become a popular topic for those writing about asset management (Bevilacqua and Braglia, 2000, Shyjith et al., 2008, Medina-Oliva et al., 2015b). The main purpose of such models is to identify the most appropriate maintenance strategy whilst achieving adequate trade-offs between different criteria. In fact, such models are
useful when asset managers need to decide on expensive maintenance strategies such as design out maintenance (DOM) and condition based monitoring (CBM).

In the past decades, due to some major industrial failures such as Fukushima Nuclear disaster, BP Deepwater Horizon, BP Texas City, many decision-making approaches for maintenance strategy have been criticized for not considering maintenance management as a strategic concern.

On the other hand, due to tightly-controlled operational expenditure limits, maintenance managers are more under pressure to reduce the cost of maintenance whilst achieving an optimum level of downtime, safety, reliability and risk. In fact identifying such trade-offs was believed to be one the most challenging parts of decision-making in any maintenance department. Even though many papers have proposed a decision-making model for selecting a maintenance strategy, there is a common limitation among all previous studies which almost none considered decision making for maintenance strategy as a strategic concern.

The first group of methods has considered maintenance management from an operational level and the main focus was to address the concern of production and maintenance managers. Therefore, criteria such as mean time between failure (MTBF) and mean time to repair (MTTR) have been taken into account to classify the criticality of equipment in deciding on a maintenance strategy (Labib, 2004). However, such approaches might be appropriate for manufacturing industries but they are not adequate enough for the oil and gas industry as they might not reflect the real problems in the plant. Considering only two criteria for identifying the criticality level of equipment may not address concerns over safety and risk and many other issues. Such a model seems to be oversimplified if it were to be implemented in the energy sector.
Many academic attempts have been made to improve such decision-making models. (Burhanuddin et al., 2011) argue that DMG ignored the effect of cost in a maintenance problem and proposed a cost analysis to DMG. More importantly, (Ishizaka and Nemery, 2014) argue that DMG is incapable of adding unlimited criteria into its decision-making phase in which a decision model was proposed using the ELECTRE-SORT approach that added two other criteria: spare parts cost and bottleneck to DMG proposed by (Labib, 2004). Such academic attempts to modify proposed models provide sufficient evidence that there is a need for strategic development of current approaches in the literature.

It is the aim of this research to tackle these current gaps in the literature. The Strategic Decision Making Model (SDMM) proposes to bridge these gaps to enable decision-makers to deal with maintenance management from a more strategic perspective whilst achieving an operational perspective. The case study approach was used to test the effectiveness of the proposal.

Given that the strategic concept is a long term one by its nature, validation of any strategic model might require a decade, especially if the proposed model has industrial application. In contrast, operational models can be validated in one year or less. Therefore, a reverse approach has been considered to validate the usefulness of the model. In fact, learning from the failure approach has been considered to demonstrate how SDMM can be implemented within oil and gas assets.

The approach was tested in an oil process plant in the UK where there was a need to implement condition based maintenance techniques in a cost-effective manner from a more strategic perspective whilst considering the effect of safety.
Section 5.2 discusses the application of AI and MACM for SDMM development. Section 5.3 discusses the model implementation. Section 5.4 discusses the research findings. Finally, section 5.5 concludes the whole chapter.

5.2- SDMM and its development process

5.2.1- Critical thinking

It is important to understand the importance of any decision and its consequences within an organisation. There have been many elements involved in decision-making for selecting critical components and hence maintenance strategy.

As Pareto Analysis suggests, one could argue that almost 80% of problems associated with industrial assets come from 20% of machines. Many asset managers believe that the top 20% of problematic machines have been identified appropriately. However, such assets are still experiencing catastrophic incidents (CSB, 2005). In fact, investing a maintenance budget in the wrong place can lead asset managers to believe that they have invested in the right place for safe and reliable operation.

The term criticality might have different meanings according to different manager’s perspective within an industrial plant (Qi et al., 2015). For example, if an asset manager asked middle managers (i.e. safety, risk, reliability, production, maintenance and finance managers) to provide a list of top ten critical items for investment in an oil refinery plant these would be different. Safety managers might rank the most critical items as a consequence of an item’s failure whilst a risk manager might be concerned about the likelihood of failure. Similarly, a maintenance manager might shortlist the components that have a higher failure rate whilst the main concern of a production manager is to reduce downtime so his main focus would be on those items whose failure causes an extended downtime. In
contrast, the concern of a reliability manager is over the pattern of failures for each component. (CSB, 2005)

More importantly, as the oil price has dropped to less than half in recent years, the concerns of the financial manager cannot be ignored as there is a need to think about operational expenditure, capital expenditure, return on investment and production loss. Therefore, inevitably financial concerns need to be taken into account whilst deciding on maintenance strategy.

In fact, for many industrial plants considered the criticality of equipment from one or two concerns which is mainly production and safety and they failed to combine the view of all experts while deciding on the final list as the most critical part of the plant. Therefore, this has been found to be one of the most challenging parts of such decision-making. As such, the question is how does the asset manager decide on the final list of criticality whilst combining the view of all associated managers?

![Figure 28-The Proposed Strategic Decision Making Model](image-url)
5.2.2- Strategic concepts in maintenance management

There have been few academic attempts in the literature to discuss the strategic concept of maintenance management. (Tsang, 1998) proposed a strategic approach to measure maintenance performance using balance score cards. Subsequently, he (Tsang, 2002) discussed four strategic dimensions of maintenance management but both studies failed to discuss the challenges of criticality assessment methods as a strategic concern for maintenance management.

Even though during the last decade there has been good academic and industrial collaboration to investigate strategic dimensions of maintenance management, more still remains to be done. The strategic dimension of maintenance and asset management not only needs to be focused on mathematical modelling for quantitative analysis of relative data but also requires it to track how a continues improvement can be achieved from an overall business perspective by analysing qualitative data. (Murthy et al., 2002) noted that the University of Queensland formed a research group on reliability engineering and risk management to investigate maintenance management from a strategic perspective. This closely collaborated with industry to consider strategic concern towards maintenance management.

Even though researches are growing gradually to address this strategic concern, (Mather, 2005a) discussed the concepts of maintenance score card (Eti et al., 2006) suggests the existing of 5 dimensions to strategic maintenance management in Nigerian industries namely management policy, support process, maintenance methodology, culture, organisation and work structuring. However, understanding the strategic demonstrations of maintenance management falls well short of what was expected by Kaplan and Norton, who were pioneers of strategic management.
The proposed SDMM is an approach to introduce a new school of thought for discussing the strategic concept of maintenance management.

5.2.3- SDMM phase 1: The application of fuzzy logic

The applications of fuzzy logic have received attention from researchers and practitioners in varieties of engineering disciplines ranging from intelligent traffic light controllers (Center and Semarak, 1996) to very complex robotic problems (Hassanzadeh et al., 2014). Fuzzy logic will be used mainly in decision-making problems. The applications of fuzzy logic have received much attention in maintenance management, ranging from maintenance strategy implementation (Sharma et al., 2005a) to maintenance optimisation problems (Sahoo et al., 2014). Many of its applications have been successfully applied in maintenance management. (Zadeh and Kacprzyk, 1992) discussed how fuzzy logic deals with uncertainties during decision-making problems. (Braglia et al., 2003) proposed a fuzzy criticality assessment method for FMECA and, similarly, (Pillay and Wang, 2003) used fuzzy logic to modify and improve the FMEA in practice. (Guo et al., 2009) proposed a fuzzy approach to improve the criticality assessment method used in RCM for petrochemical equipment in which a neural network algorithm was adapted to decide on the maintenance strategy. The inputs of the fuzzy model comprise four influential factors: maintenance cost, environmental effect, safety and production loss. More recently, (Qi et al., 2015) proposed a fuzzy criticality assessment method for optimising maintenance management.

There are many way in which strategic dimensions of maintenance management can be investigated. The main contribution of the present study is to improve the criticality assessment methods and decision-making for selecting critical equipment from four perspectives proposed by (Kaplan and Norton, 2001) for strategic
management i.e. financial perspective, customer perspective, internal business perspective and learning and growth. The similar terms have been defined for these four perspectives which might be more relevant to the concept of maintenance management.

Fuzzy logic is applied on each of these dimensions individually. In fact, each dimension represents the view of one or two managers. Figure 28 illustrates the criteria that have been considered for each dimension. For instance, the operational dimension will investigate both the view of the maintenance and production managers which is similar to what was proposed by (Labib, 2004) whilst the financial perspective will represent the criteria that have been considered in actual petrochemical practice (Qi et al., 2015), i.e. production loss and maintenance cost as criteria which reflect the concerns of asset managers. On the other hand, the customer perspective, which can be referred to as the safety perspective, needs to reflect the concerns of risk and safety managers, i.e. the likelihood and consequences of failures.

Finally, the learning and growth perspective, which can be referred to as the technical perspective, is one in which the importance of equipment needs to be analysed from two perspectives: within the whole reliability block diagram (RBD) of the plant and also its pattern of failure (P.F).
Figure 29-Strategic dimensions of the proposed SDMM

**Safety perspective (customer perspective)**

Customer perspective plays an essential role in strategic management. One of the main purposes of maintenance management in the oil and gas industry is to provide a safe operation which avoids any health and safety issues. In fact, the main concern is for the operation of such assets to have no effect on the environment. Therefore, it is important to investigate the criticality of equipment with respect to safety and its consequences to the environment, especially in recent decades where there have been many catastrophic incidents involving oil and gas assets. Table-4 illustrates the consequence of failure with respect to safety.

Even though researches pay particular attention to financial and technical perspectives of maintenance management however the effect of safety had been eliminated in many of published papers and also even those models that address the concern of safety failed to look at the safety on its own rather providing a weighting scale for safety factor and simply add it up with some financial concerns such as
production loss cost and maintenance cost (Qi et al., 2015). However maintenance models need to look at safety on its own rather providing more weighting for safety during the criticality assessment method and then adding this factor with financial or any other concerns.

Table 4-The classification of equipment with respect to consequence of failure

<table>
<thead>
<tr>
<th>Effect of Health and Safety</th>
<th>Description</th>
<th>Membership Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slightly Hazardous (SH)</td>
<td>Potential first aid injury on site</td>
<td>Low</td>
</tr>
<tr>
<td>Hazardous (H)</td>
<td>Potential serious permanent injury</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>Potential offsite injury</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Local environmental damage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>offsite odour complaints</td>
<td></td>
</tr>
<tr>
<td>Deadly Hazardous (DH)</td>
<td>Potential loss of life on site</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Potential serious offsite injuries</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Long-term environmental damage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Regulated release occurs causing long-term environmental damage</td>
<td></td>
</tr>
</tbody>
</table>

There are many criticality assessment approaches that compare safety with other financial factors however such a comparison has become illegal. One of the biggest advantages of the proposed SDMM is that it deals with safety on its own.

In fact, in order to evaluate the criticality matrix w.r.t safety, the consequences of failures assessed by the environmental impact of failure with respect to its likelihood of failure. Table-5 presents how quantitative failure analysis might be used to understand the likelihood of failure.
The values that representing the quantitative failure probability in Table-5 assumed to be for oil and gas industry and they are subjected to change if they are to be considered for nuclear industry. To elaborate more on what does quantitative failure probability means, this can be explain that if a curtain duty of machine fail to function on the demand for a period of time. For instance if a reactor failed to operate once for every 8 times of demand within a period of time e.g. a month then it will be consider to be as highly critical in terms of quantitative failure probability.

Once particular equipment is classified with respect to both criteria then there are specific rules which need to be assigned according to the expert’s knowledge about safety issues. In fact, safety will be evaluated by combining both quantitative and qualitative data. As far as the identification of the environmental impact requires a subjective judgment of a decision-maker, in some cases a slight change in the subjective judgment could change the level of criticality. Therefore fuzzy logic is applied to overcome such a concern.
The rule evaluation phase of safety perspective need to address the concern of safety manager therefore as Table-6 presents very high criticality have been defined for components that their consequence of failure identify to be deadly Hazardous. Even if the likelihood of such failure is low the criticality has been defined to be very highly critical. Total numbers of 9 rules define for safety perspective according to Table-6.

<table>
<thead>
<tr>
<th>Consequence of failure</th>
<th>Slightly Hazardous (L)</th>
<th>Hazardous (M)</th>
<th>Deadly Hazardous (H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relatively few failures (L)</td>
<td>Very Low Critical</td>
<td>Low Critical</td>
<td>Very High Critical</td>
</tr>
<tr>
<td>Occasional failures (M)</td>
<td>Low Critical</td>
<td>Medium Critical</td>
<td>Very High Critical</td>
</tr>
<tr>
<td>Repeated failures (H)</td>
<td>Medium Critical</td>
<td>High Critical</td>
<td>Very High Critical</td>
</tr>
</tbody>
</table>

The figures 30 and 31 indicate the membership functions (MFs) defined for likelihood of failure and consequence of failure respectively. These MFs will be considered as input for identifying the criticality of equipment with respective to safety perspective.
In fact the proposed model aimed to demonstrate an approach rather than suggesting the same numerical values or rules to be applied for specific business concepts. Therefore the values and rules are flexible depending on the industry, culture of asset management and other factors.

In order to present how the model works, considering a particular component that has been identified to have low likelihood of failure i.e. 22.5% and high consequences of failure i.e. 70.5% as presented in figure-5. Such component fires out the input MFs for likelihood of failure that are associated with rule number 1, 2, and 3 and also it fires out the input MFs for consequence of failure that are associated with rule number 3, 6 and 9. Figure-5 and 6 illustrated the inputs and outputs considered and the criticality level that obtained for this particular component from safety perspective.
Once the criticality identified from safety perspective then the same component need to be analysis from technical perspective, operational perspective and financial perspective. Figure 34 present the profile of the fuzzy inference representing the decision surface results from safety perspective. The criticality level for safety perspective can be identify by drawing a perpendicular line from the crossing point of lines coming from likelihood and consequence of failure to the surface fuzzy results.
The similar processes of decision making have been considered for the other three perspectives with different values and criteria. Therefore the same component will be assessed from the other three perspectives and it might receive different criticality levels from the view of different managers e.g. production manager, maintenance manager, reliability manager and financial manager. The question is which one is the most important and how these surface results can be combined while focusing on safety on its own and not just simply averaging the surface results of these four perspectives and proposed the overall criticality level. In fact simply averaging the result of different managers is what happens in many industrial plants and the best they assign more weights for safety and add it up with other criteria (Qi et al., 2015). It means that safety is still comparing with financial and many other factors which are not acceptable any more especially for industries such as nuclear, oil and gas. This chapter will comprehensively provide a solution for such challenges where the
capability of rule evaluation phase of fuzzy logic has been playing significant roles in this matter.

**Technical perspective (learning and growth)**
One of the best ways to learn from failures is to look at the technical perspective behind each equipment failure. Many techniques have been developed to improve the understanding behaviour of failures such as reliability block diagrams (RBD), fault three analysis (FTA), Weibull analysis. In fact, one of the ways to achieve continues improvement is to understand the pattern of failure and investigate whether the associated failure is because of factors such as inappropriate installation, i.e. infant failure, or if it relates to random failure or if the equipment has failed because it has reached to its wear out stage.

On the other hand, it is crucial to understand the importance of equipment failure with respect to the whole RBD of a system. Therefore, the two main criteria that have been considered to investigate technical dimensions of equipment are proposed to be the pattern in which components fail and its importance for the whole RBD. The table 7 and 8 describe how the fuzzification for technical perspective has been defined in fuzzy logic tool box.

There might be different engineering approaches to investigate the pattern of failure or even expert judgments. Weibull analysis is one that has received a great deal of attention compared to other techniques.
Table 7: The classification of equipment in terms of their pattern of failures

<table>
<thead>
<tr>
<th>The pattern of failure</th>
<th>Description</th>
<th>Membership Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infant failure</td>
<td>Due to inappropriate installation</td>
<td>Low</td>
</tr>
<tr>
<td>Random Failure</td>
<td>Any sort of failure that might result in random failure</td>
<td>Medium</td>
</tr>
<tr>
<td>Wear out failure</td>
<td>Once the useful life of equipment is close to the end</td>
<td>High</td>
</tr>
</tbody>
</table>

Once the pattern of failure is identified for equipment then it is important to investigate their contribution to the main production process. The knowledge of experts can be used to construct an appropriate RBD. Accordingly, depending on a few other criteria such as whether the equipment has got a standby spare installed and its bottleneck position then the component failure can be classified into three different groups. Table 8 demonstrates a possible approach of RBD classification in which whether the equipment failure effects locally i.e. not directly affect the mechanical performance of production process, or it could affect the system or surrounding unit which would result in lowering the mechanical performance of facilities, or it could even affect the whole mechanical performance of the plant.

Table 8: Classification of equipment with respect to the reliability block diagram

<table>
<thead>
<tr>
<th>The importance of machine w.r.t. RBD</th>
<th>Description</th>
<th>Membership function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local effect</td>
<td>The equipment not working but only effect locally</td>
<td>Low</td>
</tr>
<tr>
<td>System effect</td>
<td>Lowering the mechanical performance of a unit</td>
<td>Medium</td>
</tr>
<tr>
<td>Plant effect</td>
<td>Lowering the mechanical performance of a plant</td>
<td>High</td>
</tr>
</tbody>
</table>
Once a particular equipment is classified with respect to both criteria then there are certain rules which need to be assign to indicate the criticality of equipment with respect to technical perspective. It is important to note that the expert’s knowledge can be used to form these rules.

Table-9 demonstrates the way in which these rules can be generated to classify equipment criticality in terms of pattern of failure and the machine’s importance with respect to RBD. For instance, for a particular piece of equipment if the associated failure effect is local and it has an infant failure then its criticality will be classified as very low. In contrast, if the associated failure of another piece of equipment is due to wear out and it could affect the plant then its criticality will be considered to be very high. Figure-35 presents the inputs that have been considered for technical perspective in fuzzy logic.

<table>
<thead>
<tr>
<th>RBD</th>
<th>P.F</th>
<th>Effect</th>
<th>Effects on System</th>
<th>Effects on Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infant</td>
<td>Infant Failure</td>
<td>Very Low</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Random</td>
<td>Random Failure</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Wear Out</td>
<td>Wear Out Failure</td>
<td>Medium</td>
<td>High</td>
<td>Very High</td>
</tr>
</tbody>
</table>

Figure 36-Structure of fuzzy logic for criticality-w.r.t.-Technical Perspective
The figure 36 and 37 indicates the membership functions (MFs) defined for pattern of failure and importance of machine with respect to reliability block diagram respectively. These MFs will be considered as input for identifying the criticality of equipment with respective to technical perspective.

Let’s consider the result of reliability analysis indicates that the same machine which analysed from safety perspective is in its wear out stage (0.765 out of 1) and the important of machine with respect to RBD identified to have effect on plant (0.81) as presented in figure-38. Therefore such component fires out the input MFs for pattern of failure that are associated with rule number 3, 6, and 9 and also it fires out the input MFs for importance of machine w.r.t that are associated with rule number 7, 8 and 9.
Figure 39-Illustrated the input and outputs for technical perspective

Figure 38 and 39 illustrated the inputs and outputs considered and the criticality level that obtained for this particular component from technical perspective.

Figure 40-The criticality level with respect to technical perspective

Once the criticality identified from technical perspective then the same component need to be analysis from operational perspective and financial perspective. Figure 40 presents the profile of the fuzzy inference representing the technical perspective.
One of the most challenging parts of any industrial plant is to find the optimum point of operation and maintenance. Assets like oil production have posed a big challenge for operation and maintenance managers as one is interested in reducing downtime as much as possible whilst the other is looking to reduce failure frequency. Therefore, criteria such as mean time to repair and mean time between failures are the most common criteria that have been used (Labib, 1998) to optimise the view of maintenance and operation managers.

Similarly, SDMM uses both criteria, i.e. MTTR and MTBF, to classify equipment criticality from operational perspective. In order to measure these two criteria, it is important to consider a timeframe in which such criteria will be assessed, either
quarterly, yearly or every few years. Table-10 demonstrates typical values that might be considered for identifying different levels of criticality in terms of failure frequency. Such values can best be obtained from the knowledge of experts who are working in the same industries. For instance if such model is to be implemented in nuclear industry then more than 2 failure per 100 year might be considered as highly critical.

<table>
<thead>
<tr>
<th>Frequency (No. of)</th>
<th>Description</th>
<th>Membership Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>If it fails less than 5 times (p/y)</td>
<td>Low</td>
</tr>
<tr>
<td>5-10</td>
<td>If it fails 5 to 10 times (p/y)</td>
<td>Medium</td>
</tr>
<tr>
<td>+10</td>
<td>Failure more than 10 times (p/y)</td>
<td>High</td>
</tr>
</tbody>
</table>

If the proposed model aims to investigate the performance of assets from a strategic perspective, the performance of equipment should be tracked at least every month and the performance of equipment with respect to MTTR and MTBF should be compared with previous records every quarter. In fact these MTTR and MTBF can be obtained from computerized maintenance management systems CMMS used in a particular refinery or process plant.

Table-11 defines regions for low, medium and high downtimes which can be modified as the nature of the industry varies from one to another. Also, the culture of organisation could change these values. For instance, Japanese companies might consider 1 to 10 (hours/year) of downtime for a plant as medium or even high downtime.
Once the criticality of a particular component is identified in terms of MTTR and MTBF then there are particular rules which need to be assigned for evaluating the criticality level.

Table 12 demonstrates the way in which these rules can be generated to classify component criticality in terms of downtime and failure frequency. For instance, there are number of component that are not failing very frequently but when it fails it will cause a big downtime therefor the criticality of such component will be classified as very high. Figure 41 presents the inputs that have been considered for operational perspective in fuzzy logic.

<table>
<thead>
<tr>
<th>Downtime</th>
<th>Description</th>
<th>Membership Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10 hr</td>
<td>Between 0 – 10 hr per year</td>
<td>Low</td>
</tr>
<tr>
<td>10-24 hr</td>
<td>Between 10-24 hr per year</td>
<td>Medium</td>
</tr>
<tr>
<td>+24 hr</td>
<td>More than day per year</td>
<td>High</td>
</tr>
</tbody>
</table>

The figure 42 and 43 indicate the membership functions (MFs) defined for failure frequency and downtime. These MFs will be considered as input for identifying the criticality of equipment with respective to technical perspective.
Considering the data obtained from CMMS for the machine discussed earlier indicates low failure frequency (4) and it causes a high down time which is more than day (24.1 hr) as presented in figure-44. Such component fires out the input MFs for failure frequency that are associated with rule number 1 to 6 also it fires out the input MFs for downtime that are associated with rule number 3, 6 and 9.
Figure 45-Illustrated the input and outputs for operational perspective

Figure 44 and 45 illustrated the inputs and outputs considered and the criticality level that obtained for this particular component from operational perspective.

Figure 46-The criticality level with respect to operational perspective

Once the criticality identified from operational perspective then the same component need to be analysis from financial perspective. Figure-46 presents the profile of the fuzzy inference representing operational perspective.
Financial Perspective

The financial perspective in maintenance management refers to the concerns in such areas as production cost, maintenance cost, spare part cost and production loss cost. However, in order to identify the critical components, there are certain criteria that need particular attention. In fact, the financial perspective deals with concerns raised from asset managers. There are two main concerns that almost all refineries or process plants need to take into account: production loss cost and maintenance cost. Therefore, it is necessary to investigate using a different ‘what if’ analysis for equipment failure to understand the importance of these two criteria for a specific piece of equipment.

These two criteria have been considered as inputs to fuzzy logic which is defined for the financial perspective. In order to define the boundaries for membership function...
(MF) within each criterion, the numerical values for a chemical plant in the UK have been used to illustrate how the fuzzy model can be defined. These boundaries can be updated depending on the nature of the plant or the culture of asset management. Table 13 presents values for production cost loss and Table 14 presents the values defined for maintenance cost.

**Table 13-Classification of equipment with respect to production loss [adopted from (Qi et al., 2015)]**

<table>
<thead>
<tr>
<th>Effect on Business</th>
<th>Description</th>
<th>Membership Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Effect</td>
<td>1 to 8 hr shutdown resulting in £5000-£50000 business loss</td>
<td>Low</td>
</tr>
<tr>
<td>Medium Effect</td>
<td>8-24 hr shutdown resulting in £50000-£100000 business loss</td>
<td>Medium</td>
</tr>
<tr>
<td>High Effect</td>
<td>More than 24hr shutdown resulting in more than £100000 business loss</td>
<td>High</td>
</tr>
</tbody>
</table>

**Table 14-Classification of equipment with respect to maintenance cost**

<table>
<thead>
<tr>
<th>Annual maintenance cost</th>
<th>Description</th>
<th>Membership Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Cost</td>
<td>£10000 to £20000 (p/y)</td>
<td>Low</td>
</tr>
<tr>
<td>Medium Cost</td>
<td>£20000 -£500000 (p/y)</td>
<td>Medium</td>
</tr>
<tr>
<td>High Cost</td>
<td>More than £50000 (p/y)</td>
<td>High</td>
</tr>
</tbody>
</table>

Once particular equipment is classified with respect to both criteria then there are specific rules which might be assigned according to the asset manager’s point of view. Table-15 demonstrates the way in which such rules have been generated.
Table 15-Rule generating process for equipment criticality w.r.t production loss and maintenance cost

<table>
<thead>
<tr>
<th>Production Loss vs Maintenance Cost</th>
<th>Low effect</th>
<th>Medium effect</th>
<th>High effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Cost</td>
<td>Very Low Critical</td>
<td>Low Critical</td>
<td>High Critical</td>
</tr>
<tr>
<td>Medium Cost</td>
<td>Low Critical</td>
<td>Medium Critical</td>
<td>High Critical</td>
</tr>
<tr>
<td>High Cost</td>
<td>Medium Critical</td>
<td>High Critical</td>
<td>Very High Critical</td>
</tr>
</tbody>
</table>

Figure 47 illustrated the inputs that considered as inputs in fuzzy logic for financial perspective that are maintenance cost and production cost loss.

![Figure 48-The fuzzy inputs for financial perspective](image)

Figures 48 and 49 indicate the membership functions (MFs) defined for maintenance cost and production cost loss respectively. These MFs will be considered as input for identifying the criticality of equipment with respective to financial perspective.
Figure 50 illustrated that if the same component has the low maintenance cost £14300 per year but the consequences of its failure in terms of production loss is very high more than £100000 per day then this component is highly critical from financial perspective. Such component fires out the input MFs for production loss that are associated with rule number 7, 8, and 9 and also it fires out the input MFs for maintenance cost that are associated with rule number 1, 4 and 7.

Figures 50 and 51 illustrated the inputs and outputs considered and the criticality level that obtained for this particular component from financial perspective.
Once the criticality identified from financial perspective then all the output results obtained from each perspective will be consider as an input to the strategic fuzzy logic where the overall criticality equipment will be identify while combining the results of these four perspectives. Figure 52 presents the profile of the fuzzy inference representing for financial perspective.
Strategic Fuzzy logic Model

Once the criticality levels have been identified from four different perspectives, the main question is which of these perspectives are the most important and how these 4 different criticality levels can be combined?

The strategic fuzzy logic implemented to identify the overall criticality level of equipment while considering safety on its own. In fact, the strategic fuzzy logic model provides an opportunity to combine the views of all managers to obtain the overall criticality of equipment.

As far as some inputs require subjective judgements of decision maker, there is a degree of uncertainty within each perspective, whilst the same uncertainty exists between these four dimensions. In fact, the first stage of the fuzzy approach just
deals with uncertainties between the view of managers within each perspective like production and maintenance managers for operational perspective. Hence, there are still uncertainties between production manager and safety manager and so on. Therefore, it is necessary to apply the concept of fuzzy logic to address the uncertainties that exist between one perspective and the other three perspectives.

Strategic fuzzy logic requires combining the results obtained from de-fuzzification of the four criticality perspectives. In fact, the result obtained from the de-fuzzification phase of four strategic dimensions will be considered as an input to strategic fuzzy logic.

Initially, there are 4 inputs (i.e. fuzzy logic outputs of each perspectives) with 5 MF defined for strategic fuzzy logic, meaning $5^4$ rules, i.e. 625 rules. However, as the number of rules increased the subjective judgments of decision-makers reduce the accuracy of results and introduce a degree of uncertainty. Therefore, in order to avoid such concern it was decided to reduce the number of rules. The initial output of each perspective i.e. 5 membership functions reduce to 3 membership function. It means that very low and low M.Fs considered as being Low, medium MFs remained as medium and high and very high MFs considered to be high. Consequently $3^4$ rules needed to be defined for strategic fuzzy logic, i.e. 81. Figure 53 presents the inputs and outputs of strategic fuzzy logic model.
**Rule evaluation approach for strategic fuzzy logic model**

The following categories have been proposed to establish a method for a decision-maker to generate rules:

- **Category A**: If all and/or at least 3 out of 4 MFs are High Critical (H.C) then the output membership functions would be Very High Critical (VHC)

- **Category B**: if at least 2 out of 4 MFs are HC then the output MF is High Critical (H.C)

- **Category C**: if at least 1 (i.e. safety) out of 4 MFs is HC then output MF is High Critical (H.C)

- **Category D**: if all or at least 3 out of 4 MFs are Medium Critical (M.C) then the output MF is High Critical (H.C)

- **Category E**: if at least 2 out of 4 MFs are MC then the output MF is MC

- **Category F**: if all and/or at least 3 out of 4 MFs are LC then the output MF is LC or Non Critical

Table 16, table 17, table 18, table 19 and table 20 presenting the way in which rules need to be generated for fuzzy logic.
• Category A: If All and/or at least 3 of out 4 MFs are (highly critical) H.C then the output membership functions is Very High Critical (V.H.C)

Table 16-Category A: If All and/or at least 3 of out 4 MFs are (Very highly critical) V.H.C

As it can be seen in the table 16 the rule number one is when 4 of the membership function is H in which the output of strategic fuzzy logic will be defined to be very highly critical.

As far as the category A is looking for at least 3 membership function to be highly critical therefore the rule number 2 defined as when safety, financial and operational perspective considered to be high and technical perspective to be medium.

Similarly the rule number 3 has the same logic but the only different is its technical perspective that is low. In fact the membership functions that have been highlighted with red colure address the minimum requirement of each category.
- Category B: if at least 2 of out 4 MFs (Membership Functions) are H.C then the output MF is Critical (C)

Table 17 - Category B: if at least 2 of out 4 MFs (Membership Functions) are H.C

(High priority components) If at least 2 out of 4MF are **High critical** output MF is **Critical**

<table>
<thead>
<tr>
<th>Rule No.</th>
<th>Safety Perspective</th>
<th>Financial Perspective</th>
<th>Operational Perspective</th>
<th>Technical Perspective</th>
<th>Output MFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rule.No 10</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 11</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>L</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 12</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 13</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 14</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 15</td>
<td>H</td>
<td>M</td>
<td>L</td>
<td>H</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 16</td>
<td>H</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 17</td>
<td>M</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 18</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 19</td>
<td>M</td>
<td>L</td>
<td>H</td>
<td>H</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 20</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 21</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td>H</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 21</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 23</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 24</td>
<td>L</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 25</td>
<td>L</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 26</td>
<td>H</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 27</td>
<td>H</td>
<td>M</td>
<td>H</td>
<td>L</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 28</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 29</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>L</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 30</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td>H</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 31</td>
<td>L</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 32</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td>H</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 33</td>
<td>L</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>H.C</td>
</tr>
</tbody>
</table>
• Category C: if at least 1 (i.e. safety) out of 4 MFs is H.C then Output MF is critical

Table 18-Category C: if at least 1 out of 4 M(Membership Functions) is Critical

High priority :if 1 MF (i.e. Safety) out of 4 MF to be High critical then output MF is Critical

<table>
<thead>
<tr>
<th>Rule No.</th>
<th>Safety Perspective</th>
<th>Financial Perspective</th>
<th>Operational Perspective</th>
<th>Technical Perspective</th>
<th>Output MFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rule.No 34</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 35</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>L</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 36</td>
<td>H</td>
<td>M</td>
<td>L</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 37</td>
<td>H</td>
<td>M</td>
<td>L</td>
<td>L</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 38</td>
<td>H</td>
<td>L</td>
<td>M</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 39</td>
<td>H</td>
<td>L</td>
<td>M</td>
<td>L</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 40</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 41</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>H.C</td>
</tr>
</tbody>
</table>

• Category D: if all and/or at least 3 out of 4 MFs are MC then the output MF is Critical

Table 19-Category D:if at least 4 and/or 3 out of 4MF to be Medium critical then output MF is Critical

(High priority): ;if at least 4 and/or 3 out of 4MF to be Medium critical then output MF is Critical

<table>
<thead>
<tr>
<th>Rule No.</th>
<th>Safety Perspective</th>
<th>Financial Perspective</th>
<th>Operational Perspective</th>
<th>Technical Perspective</th>
<th>Output MFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rule.No 42</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 43</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 44</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>L</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 45</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 46</td>
<td>M</td>
<td>M</td>
<td>L</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 47</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 48</td>
<td>M</td>
<td>L</td>
<td>M</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 49</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule.No 50</td>
<td>L</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>H.C</td>
</tr>
</tbody>
</table>
- Category E: if at least 2 out of 4 MFs are MC then the output MF is MC

Table 20 - Category E (Medium priority) if at least 2 out of 4 MF are Medium critical output MF is Medium Critical

<table>
<thead>
<tr>
<th>Rule No.</th>
<th>Safety Perspective</th>
<th>Financial Perspective</th>
<th>Operational Perspective</th>
<th>Technical Perspective</th>
<th>Output MFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rule No. 51</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 52</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>L</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 53</td>
<td>M</td>
<td>M</td>
<td>L</td>
<td>H</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 54</td>
<td>M</td>
<td>M</td>
<td>L</td>
<td>L</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 55</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 56</td>
<td>M</td>
<td>H</td>
<td>L</td>
<td>M</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 57</td>
<td>M</td>
<td>L</td>
<td>H</td>
<td>M</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 58</td>
<td>M</td>
<td>L</td>
<td>L</td>
<td>M</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 59</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule No. 60</td>
<td>H</td>
<td>L</td>
<td>M</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule No. 61</td>
<td>L</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 62</td>
<td>L</td>
<td>L</td>
<td>M</td>
<td>M</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 63</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule No. 64</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>L</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule No. 65</td>
<td>L</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 66</td>
<td>L</td>
<td>M</td>
<td>M</td>
<td>L</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 67</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td>H</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 68</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td>L</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 69</td>
<td>M</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 70</td>
<td>M</td>
<td>L</td>
<td>M</td>
<td>L</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 71</td>
<td>H</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule No. 72</td>
<td>H</td>
<td>M</td>
<td>L</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>Rule No. 73</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td>M.C</td>
</tr>
<tr>
<td>Rule No. 74</td>
<td>L</td>
<td>M</td>
<td>L</td>
<td>M</td>
<td>M.C</td>
</tr>
</tbody>
</table>
The approach of using linguistic terms to generate rules in fuzzy logic is called the roughness method. Here, the term ‘at least’ was used to define rules. However, there have been some issues concerns about safety whilst generating these rules. There are numbers of rules which need to be excluded from each category to address the concern of safety appropriately.

The above rules have been generated according to the concern of oil and gas industry. Because there have been many catastrophic incidents in the last couple of decades in this industry the SDMM give high priority to the concern of safety. Therefore the rule that contradicts with safety concern while applying the logic of each category was not followed the logic dictated with the category and the output membership function defined to be critical. As table-20 illustrated such rules i.e. rule number 59, 60, 63, 64, 71 and 72 excluded to follow the logic of the category and the overall criticality defined to be high critical which have been highlighted with red and yellow colours.

- Category F: if all and/or at least 3 out of 4 MFs are LC then the output MF is LC or Non Critical

<table>
<thead>
<tr>
<th>Rule No.</th>
<th>Safety Perspective</th>
<th>financial Perspective</th>
<th>Operational Perspective</th>
<th>Technical Perspective</th>
<th>Output MFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rule.No 75</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>N.C</td>
</tr>
<tr>
<td>Rule.No 76</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td>L.C</td>
</tr>
<tr>
<td>Rule.No 77</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>M</td>
<td>L.C</td>
</tr>
<tr>
<td>Rule.No 78</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td>L</td>
<td>L.C</td>
</tr>
<tr>
<td>Rule.No 79</td>
<td>L</td>
<td>L</td>
<td>M</td>
<td>L</td>
<td>L.C</td>
</tr>
<tr>
<td>Rule.No 80</td>
<td>L</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td>L.C</td>
</tr>
<tr>
<td>Rule.No 81</td>
<td>L</td>
<td>M</td>
<td>L</td>
<td>L</td>
<td>L.C</td>
</tr>
</tbody>
</table>
Discussing the output of the category F it was also possible to define other two rules i.e. if the following 3 out of 4 MF to be low critical then output MF here needs to be Critical due to the safety concern which is not following the logic of category F as it is illustrated in table 22.

<table>
<thead>
<tr>
<th>Safety Perspective</th>
<th>Financial Perspective</th>
<th>Operational Perspective</th>
<th>Technical Perspective</th>
<th>Output MFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>H.C</td>
</tr>
<tr>
<td>M</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>H.C</td>
</tr>
</tbody>
</table>

It is worth to introduce one other category in which the culture of asset management can be more visibly define during rule generation process. Once all the above rules applied and the concern of safety dealt with appropriately then this category can be define to investigate the criticality while the safety is low. Therefore the following category can be defined.

- Category G: if safety is low then the output M.F may varies between low, medium and high critical depending on the culture of asset management

<table>
<thead>
<tr>
<th>Safety Perspective</th>
<th>Financial Perspective</th>
<th>Operational Perspective</th>
<th>Technical Perspective</th>
<th>Output MF</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>L</td>
<td>M</td>
<td>M</td>
<td>M.C</td>
</tr>
<tr>
<td>B</td>
<td>L</td>
<td>M</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>C</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>M.C</td>
</tr>
<tr>
<td>D</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>H.C</td>
</tr>
<tr>
<td>E</td>
<td>L</td>
<td>H</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>F</td>
<td>L</td>
<td>H</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>G</td>
<td>L</td>
<td>H</td>
<td>M</td>
<td>H.C</td>
</tr>
<tr>
<td>H</td>
<td>L</td>
<td>H</td>
<td>H</td>
<td>H.C</td>
</tr>
</tbody>
</table>
As it has been illustrated in the table-23, this category investigates different scenarios when the safe is low. The rule “A” assigned medium criticality if all other perspectives are medium and even if the operational perspective is high the output for overall criticality defined to be medium i.e. rule “C”, whereas if the technical perspective is high the overall criticality defined to be High i.e. rule “B” and similarly if both technical and operational are high then the overall criticality is defined to be high i.e. rule “D”.

As far as the concern of financial perspective has becoming more important due to the concern of oil prices in recent years, if the financial perspective identified to be High then the overall criticality will be defined to be high irrespective of the condition of other perspectives i.e. rules D,E,F and H. This is one way that the rules can be generated and these rules can be best generated during a group discussing with expert for a specific industry and business environment.

The trapezoidal shape considered for membership functions that indicates the range of criticality levels. Figure-54 presented the range of values that has been considered for overall criticality membership functions.

![Figure 55-The overall criticalities membership functions](image)
5.2.4- SDMM phase 2: The application of AHP

Once the criticality of equipment has been identified then the AHP can be implemented to simulate the behaviour of humans towards maintenance and asset management. Only equipment that has been defined as VHC or C are candidates for AHP implementation.

Even though many techniques such as RCM suggest a maintenance strategy based on the level of criticality, it does not indicate that such maintenance strategies have actually been implemented during plant operation. In fact, such attitudes have been observed in many organisations that have experienced catastrophic incidents such as BP Texas City where the culture of the organisation affected maintenance management.

**AHP Modelling**

The following are the steps that can be used to break down the decision-making for maintenance strategy in a hierarchical order.

- Step 1- define the goal: this means selecting the most appropriate maintenance strategy
- Step 2- define the criteria: the four perspectives of strategic decision-making have been considered. These are financial, customer, internal business and learning & growth which represent reliability, operational, cost and safety concerns.
- Step 3- define the alternative: the critical equipment has been consider for AHP implementation and so the reactive approach, i.e RTF, would not be considered as an alternative. Instead FTM, CBM and DOM are the selected options.
- Step 4- Give the relative importance of one criterion with respect to others (expert judgement). This stage is where the culture of organisation can be investigated i.e. whether organisation considers safety in the first priority or there is a culture of cost cutting.

- Step 5- Give the relative importance of alternatives with respect to each criterion. Similarly, the behaviour of asset managers can be tracked here whilst deciding on a different maintenance strategy for critical equipment.

- Step 6- Check the judgement is consistent, if not, ask the expert to revise his/her judgement. Once the judgement is made by decision-makers, the consistency of his/her subjective judgement needs to be checked through a consistency ratio and it should be less than 0.1.

There are different scenarios through which the behaviour of an organization can be investigated. Figure-55 demonstrates how a decision-making problem in selecting a maintenance strategy can be structured while considering a strategic perspective.

![Diagram of Strategic Decision-Making](image)

**Figure 56-The hierarchical view of strategic decision-making for selecting maintenance strategy**
As can be seen in Figure-55, four perspectives have been considered to analyse the culture of an organisation whilst making decisions on maintenance strategy. It is worth mentioning that because the AHP will be apply only for critical parts therefore RTF will not be recommended for such components under any circumstances. The dotted lines will present that the RTF cannot be as an alternative for decision makers.

The financial perspective refers to when the asset manager places more emphasis on cost and suggests strategies like a cost-cutting policy. A customer perspective refers to an emphasis on the concerns of safety where the asset considers safety as the first priority; the internal business perspective is concerned with downtime and the technical perspective with reliability.

Figure-30 illustrates how such a decision-making problem has been defined for the software developed for the concept of AHP which is known as the Expert Choice.

![Expert Choice view](image)

**Figure 57-The Expert Choice view for defining SDMM strategy implementation**
5.3- Approaches towards SDMM

There are two approaches to implement SDMM in practice. The first is to gather the required inputs for SDMM from an industrial plant and obtain the criticality level of each equipment based on the SDMM. Once the criticality levels are identified then the results should be compared with those components considered critical in actual practice. The different results obtained for the SDMM and the criticality assessment method used locally need to be discussed. It is not necessary to agree which result is better but rather to discuss what issues have or have not been considered in each method. In fact, this provides an opportunity for both approaches to learn from each other and improve their effectiveness. Accordingly, if any missing link is identified in SDMM then associated modification can be updated based on the need and knowledge of the people who are running the plant.

Unlike other models such DMG (Labib, 2004) in which its validation through industry takes one year or even just a few months, SDMM requires a number of years or even a decade to be validated through industry. This is because models like DMG are much more appropriate for manufacturing industries where the main concern is production rate whilst SDMM is more appropriate for the energy sector like power plants and oil and gas plants where there are multiple concerns that need to be satisfied simultaneously.

The nature of the strategic concept is a long term one. Therefore, the industrial validation of SDMM requires years of operation whilst tracking the overall performance of an asset yearly and quarterly to understand how the performance of a plant varies during each year of operation.

As far as the strategic decision is long term in its nature therefor implementing the strategic decision making model through oil and gas industry might requires more
than 5 years in which it is very difficult task within the PhD timeframe. However, case studies analyses have been used to demonstrate the usefulness of the proposed SDMM.

The case study approach focuses on case studies that have experienced a catastrophic incident. The associated data gathered through investigation reports which can be used to understand the root cause of a disaster and accordingly the critical equipment can be recognised.

Thus, SDMM is applied to the same equipment to see if the same result, i.e. the level of criticality, can be obtained. If the same result is not identified, it means that SDMM requires essential modification. If the same result is achieved, this means the proposed model is well structured to address the main issues with criticality. Consequently, the second stage of SDMM is implemented to investigate how the culture of asset management can influence the maintenance performance.

5.4-SDMM implementation for BP Texas City refinery
In order to understand how SDMM can be applied in actual practice, a second approach can be used in analysing a catastrophic incident such as the BP Texas City refinery. The first and most important step is to find the most critical components that contributed to the disaster from investigation reports. Once these are identified, specific information should be gathered on these whilst extracting data from in-depth interviews with relevant managers as well as from CMMS databases.

Regarding to the case study analysis of BT Texas city refinery, failure reports was available in the public domain so identifying the critical components that contributed to the disaster was not a difficult task. However, it was difficult to discover the values that needed to be considered as inputs to SDMM for each piece of equipment.
as it is not publicly-available. Therefore, the consulting oil and gas companies were approached to obtain the values that might be similar to these disasters. Table-24 gives the type of information required to be considered as an input to SDMM.

Table 24--The typical table that need to be create for components that contributed to disaster;

The case of BP Texas City refinery

<table>
<thead>
<tr>
<th>BP Texas City Disaster</th>
<th>Maintenance and Production Managers</th>
<th>Reliability and Process Managers</th>
<th>Safety and Risk Managers</th>
<th>Finance and Senior Managers</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISOM unit Explosion</td>
<td>Operational Criticality</td>
<td>Process Criticality in</td>
<td>Safety Criticality</td>
<td>Financial Criticality</td>
</tr>
<tr>
<td></td>
<td>MTTR</td>
<td>MTBF</td>
<td>RBD</td>
<td>P.F</td>
</tr>
<tr>
<td></td>
<td>Likelihood</td>
<td>Consequence</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Production loss</td>
<td>Maintenace cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine [A]: Blowdown Drum- high level alarm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine [B]: Raffinate Splitter level transmitter (LT- 5101)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine [C]: Raffinate Splitter redundant (LSH-5102) High level alarm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine [D]: Pressure vent valve for R.S Reflux Drum</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From the data gathered through in-depth interviews with oil and gas consultant companies, appropriate hypothetical scenarios were defined for components that contributed to the disaster. Table-25 classifies components A, B, C and D with respect to their pattern of failure and their importance to the whole RBD of the plant.
In order to quantify the qualitative data, the ranges of numerical values have been defined for a pattern of failure and the importance of machines with respect to RBD from 0 to 100 in which comprehensive analysis of investigation reports provide sufficient evidence that many components in the ISOM unit had moved into their wear out stage since they were installed in 1950. Also, a series of similar accidents had occurred before the main disaster. Therefore, all components A, B, C and D were identified to be in their wear out stage.

The numerical values for the wear out stage assigned to be 70 and 100, for random failure between 30 and 70, and for infant failure between 0 and 30. Table-26 outlines the decision map for identifying the most appropriate critical component with respect to pattern of failure and RBD.

**Table 25-The criteria analysis for technical perspective**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Pattern of Failure</th>
<th>Machine importance w.r.t RBD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Name of Machine</td>
<td>Bath tub curve</td>
</tr>
<tr>
<td>High 70-100 %</td>
<td>[A]</td>
<td>96%</td>
</tr>
<tr>
<td></td>
<td>[C]</td>
<td>92%</td>
</tr>
<tr>
<td></td>
<td>[D]</td>
<td>82%</td>
</tr>
<tr>
<td>Medium 30-70%</td>
<td>[B]</td>
<td>70%</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Low 0-30%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 26-Decision map in terms of P.F and RBD**

<table>
<thead>
<tr>
<th>Pattern of Failure</th>
<th>Machine importance w.r.t RBD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Non Critical</td>
<td>Low Critical</td>
</tr>
<tr>
<td>Medium</td>
<td>Low critical</td>
</tr>
<tr>
<td>High</td>
<td>Medium Critical</td>
</tr>
</tbody>
</table>
Once the inputs and rules are defined for fuzzy logic according to Table-25 and Table-26 then the decision surface result can present the criticality of each component from technical perspective.

As can be seen in Figure-57, all the components have a common characteristic, i.e. the pattern of failure that indicates to wear out. Therefore, the overall criticality is dependent on the importance of a machine to RBD; those which are considered to have more importance compared to others will receive a higher level of criticality.

Once the criticality level is identified from a technical perspective, it is time to focus on the operational perspective. In fact, the operational phase of SDMM is similar to what was proposed by DMG (Labib, 2004) but with a different range of values for

![Decision Surface Result](image-url)
what high, low and medium means for MTTR and MTBF in terms of the energy sector.

Even though MTTR and MTBF were not available for components that contributed to the BP Texas City disaster in investigation reports, but appropriate hypothetical scenarios were defined for components that contributed to the disaster. Table-27 classifies components A, B, C and D with respect to their MTTR and MTBF. The numerical values for downtime assigned were between 0-10 hrs as low, 10 to 24 as medium and more than +24 hrs as high. Similarly, a numerical value for the failure frequency is presented in Table-27.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Downtime (hrs)</th>
<th>Criteria</th>
<th>Failure Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of Machine</td>
<td>[B] 29</td>
<td>Name of Machine</td>
<td>[A] 14</td>
</tr>
<tr>
<td></td>
<td>[C] 20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High +24hr</td>
<td></td>
<td>Medium 5-10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>[C] 6</td>
<td>[B] 2</td>
</tr>
<tr>
<td>Medium 7-24 hr</td>
<td>[D] 15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low 0-7 hr</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table-28 demonstrates the decision map for identifying the most critical components with respect to down time and failure frequency.
Once the inputs and rules are defined for fuzzy logic according to Tables-27 and Table-28 then the decision surface result obtained from fuzzy logic will indicate the criticality of each component from operational perspective.
As can be seen in Figure-58, the operational criticality levels of components will be based on their historic failure data, i.e. MTTR and MTBF. Once the criticality level is identified from an operational perspective, it is important to investigate the criticality of components from a financial perspective. In fact, DMG (Labib, 2004) is incapable of dealing with financial concerns whilst at the same time making decisions on the criticality of components.

The comprehensive analysis of BP Texas City investigation reports provide sufficient evidence that the main components that caused the disaster were not working at least for more than 24 hours prior to the disaster.

For instance, the maintenance department reported that the blowdown drum needed to be replaced with the new design, and it was discussed that the pattern of failure for the blowdown drum was in its wear out stage. They suggested putting forward a business proposal for replacing the new systems for the blowdown drum. However, the asset manager of the plant refused the design out maintenance strategy for the blowdown drum and did not accept the business proposal.

The main reason given by the asset manager who rejected the offer of the maintenance department was that the business proposal did not satisfy the return on investment (ROI). In fact, the way ROI had been calculated was suffering from serious limitations.

When the different levels of the organisation do not communicate effectively, it is important for the negotiation policy of the maintenance department to address the concerns of asset managers who are focused on the daily benefits of production, i.e. financial profits. Therefore, SDMM suggests comparing the cost of maintenance
with respect to the potential production loss whilst making decisions on the level of
criticality from a financial perspective.

Table-29 presents the typical values that might be used for a refinery to classify
failure effects of components with respect to overall business impact. The numerical
values vary from £5,000 to more than £100,000 for production loss cost.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Production Loss cost</th>
<th>Machine Name</th>
<th>Business Impact</th>
<th>equivalent to £</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high</td>
<td>A, B, C, D</td>
<td>Shutdown for more than 24 hours</td>
<td>(it is equivalent to more than £100,000 loss)</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>-</td>
<td>Shutdown for 8–24 hours</td>
<td>(it is equivalent to £50,000–£100,000 business loss)</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>-</td>
<td>Shutdown for 1–8 hours</td>
<td>it is equivalent to £5000–£50,000 business loss</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>-</td>
<td>Shutdown for up to 1 hour</td>
<td>it is equivalent to business loss of up to £5000</td>
<td></td>
</tr>
<tr>
<td>Very Low</td>
<td>-</td>
<td>Less than an hour</td>
<td>No impact on production</td>
<td></td>
</tr>
</tbody>
</table>

In fact, comparing production cost lost and maintenance cost could convince
decision-makers to allocate the right budget to the maintenance department because
the potential loss of production used to be the most important concern of any asset
manager. Table-30 presents the range of values for maintenance cost which varies
from less than £1,000 to more than £50,000 per year.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Criticality</th>
<th>Machine Name</th>
<th>Maintenance cost</th>
<th>equivalent to £</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Very high</td>
<td>A</td>
<td>More than £50000 per year</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>C,B</td>
<td>£20000-£50000 per year</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>D</td>
<td>£10000-£20000 per year</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>-</td>
<td>£1000-£10000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Very Low</td>
<td>-</td>
<td>Less than £1000</td>
<td></td>
</tr>
</tbody>
</table>
Once the consequence of component failure is calculated with respect to production loss cost then such criteria can be compared with respect to the maintenance cost. Table-31 demonstrates the way rules are generated whilst considering these two criteria. It is important to note that these rules can be updated based on the needs of the plant and industry in which the knowledge of associated expert would be appreciated.

Table 31—Decision map in terms of maintenance cost and production loss cost

<table>
<thead>
<tr>
<th>Maintenance cost</th>
<th>Production Loss Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Low</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Very High</td>
<td></td>
</tr>
</tbody>
</table>

Given that the subjective judgements of experts are used to evaluate the production loss cost, slight changes of subjective judgements could change the level of criticality from one zone to another. Therefore, the fuzzy concept would be one of the approaches used to deal with such a concern.

This can be seen in Table-31, where the two red circles indicate components which are located on the border of the critical zone and the medium critical zone. In this case, a slight change in production loss cost would change the level of criticality. This in fact introduces an inappropriate belief that one could rely on what was obtained from the rule matrix while there is a degree of uncertainty that requires particular attention.
In order to overcome such concerns, the two criteria were defined as inputs to the fuzzy logic and the rule evaluation based on Table-31. The surface results obtained from fuzzy logic are presented in Figure-59.

![Decision surface result obtained for criticality level from a financial perspective](image)

According to the decision surface results obtained from fuzzy logic, machines A, B, C and D are critical items. They all share a common characteristic that they have a high impact on the business cost loss as it was stated in the failure report.

Even though the investigation report stated that the maintenance department made a request for a new design blowdown drum (i.e. machine A) no evidence was provided to that showed the maintenance department had made a reasonable attempt to convince their decision-maker to make such an investment.

As can be seen in Figure-59, Machine D has the lowest maintenance cost and lowest business impact compared to Machines A, B and C. However, it was considered a
critical piece of equipment because the function of the pressure vent valve enables the operator to vent gases manually from the splitter overhead system. This failed to open during the start-up of testing.

Once the criticality level is identified from a financial perspective, it is necessary to focus on the safety perspective which is the most important concern in the energy sector. Table-32 presents a typical safety concern within the oil and gas industry.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Consequence of Failure</th>
<th>Name of Machine</th>
<th>Safety Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Deadly Hazardous (DH)</td>
<td>A, D</td>
<td>Potential loss of life on site</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Potential serious offsite injuries</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Regulated release occurs causing long-term environmental damage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>National media coverage</td>
</tr>
<tr>
<td></td>
<td>Extremely Hazardous (EH)</td>
<td>B, C</td>
<td>Potential serious permanent injury on site</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Potential offsite injuries</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Local media coverage</td>
</tr>
<tr>
<td></td>
<td>Hazardous (H)</td>
<td>-</td>
<td>Regulated release exceeding permit conditions could occur</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Offsite odour complaint</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Regulated release occurs causing local environmental damage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Multiple offsite odour complaints</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Local media coverage</td>
</tr>
<tr>
<td></td>
<td>Slightly Hazardous (SH)</td>
<td>-</td>
<td>Potential First Aid injury on site</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non-regulated release could occur</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Local order</td>
</tr>
<tr>
<td></td>
<td>Not Hazardous (NH)</td>
<td>-</td>
<td>No hazards exist</td>
</tr>
</tbody>
</table>
Table 33-Components A, B, C and D with respect to their likelihood of failure

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Likelihood of Failure</th>
<th>Machine Name</th>
<th>Equivalent to probability of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high</td>
<td>A, B, C</td>
<td>80% to 100%</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>D</td>
<td>60% to 80%</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>-</td>
<td>40% to 60%</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>-</td>
<td>20% to 40%</td>
<td></td>
</tr>
<tr>
<td>Very Low</td>
<td>-</td>
<td>0-20%</td>
<td></td>
</tr>
</tbody>
</table>

Once the components are classified with respect to their likelihood and consequence of failure then appropriate rules should be generated to identify the criticality levels of equipment. Table-34 outlines the decision map for identifying the most appropriate critical components from a safety perspective.

Table 34-Decision map in terms of consequence and likelihood of failure

<table>
<thead>
<tr>
<th>Consequence of Failure</th>
<th>NH</th>
<th>SH</th>
<th>H</th>
<th>EH</th>
<th>DH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Low</td>
<td>Non Critical</td>
<td>Non Critical</td>
<td>Medium Critical</td>
<td>Medium Critical</td>
<td>Critical</td>
</tr>
<tr>
<td>Low</td>
<td>Non critical</td>
<td>Low Critical</td>
<td>Medium Critical</td>
<td>Medium Critical</td>
<td>Critical</td>
</tr>
<tr>
<td>Medium</td>
<td>Low Critical</td>
<td>Low Critical</td>
<td>Medium Critical</td>
<td>Critical</td>
<td>Critical</td>
</tr>
<tr>
<td>High</td>
<td>Medium Critical</td>
<td>Medium Critical</td>
<td>Critical</td>
<td>Critical</td>
<td>Highly Critical</td>
</tr>
<tr>
<td>Very High</td>
<td>Medium Critical</td>
<td>Medium Critical</td>
<td>Critical</td>
<td>Highly Critical</td>
<td>Highly Critical</td>
</tr>
</tbody>
</table>

It is worth mentioning that risk is defined as the production of likelihood and consequence of failure. Here, the main consequence and likelihood is with respect to safety concern and not any other perspective. Once the likelihood and consequence are defined as inputs to the fuzzy logic and also the rules are defined according to Table-34, the decision surface results could indicate the position of components in terms of safety criticality.
Figure 60 illustrates that blowdown drum has been identified as the most critical part of the unit which has the highest consequence and likelihood of failure. In fact, the criticality analysis from a safety perspective suggests that the blowdown has the highest risk among other components that contributed to the disaster.

The same results have been obtained through comprehensive case study analysis in which the maintenance department reported a high level of risk for the blowdown drum. It is important to note that identifying the level of criticality is half the story; the other half relates to those making decisions on asset management. In fact, many of the disasters could have been prevented if appropriate human behaviour had been adapted in the plant. Therefore, the second phase of the model utilised AHP to address this issue.
Before discussing how AHP was applied to BP Texas City to analyse the behaviour of asset managers, it is important to explain the component selected for AHP implementation.

Once the criticality level has been identified within each of the four perspectives of asset management, i.e. technical, operational, and financial and safety, then the strategic fuzzy logic needs to be applied to combine the criticality of four perspectives and suggest the absolute final overall criticality for components. Thus, all the output results obtained from these four perspectives will be considered as inputs for the strategic fuzzy logic and then the overall criticality will be assessed by using the categories of rules mentioned earlier.

In order to demonstrate how strategic decision-making selects the candidate for AHP implementation, the blowdown drum will be used as an example of how the rest of SDMM is used to identify the overall criticality and hence suggest a maintenance strategy. As stated earlier, the first category is Category A- if all and/or at least 3 out of 4 MFs are HC then the output MFs is VHC.

Earlier, the blowdown drum was found to be HC from all four perspectives, i.e. the MF of 4 out of 4, and so it will be assessed with rule number 1. The final results obtained from strategic fuzzy logic will allocate the blowdown drum to be VHC according to the table 35.
Table 35-Rule number one fires out for blowdown drum, i.e. VHC

<table>
<thead>
<tr>
<th>Input variables</th>
<th>Safety Perspective</th>
<th>Financial Perspective</th>
<th>Operational Perspective</th>
<th>Technical Perspective</th>
<th>Output Mfs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rule No. 1</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>V.H.C</td>
</tr>
<tr>
<td>Rule No. 2</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>V.H.C</td>
</tr>
<tr>
<td>Rule No. 3</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>V.H.C</td>
</tr>
<tr>
<td>Rule No. 4</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>H</td>
<td>V.H.C</td>
</tr>
<tr>
<td>Rule No. 5</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>V.H.C</td>
</tr>
<tr>
<td>Rule No. 6</td>
<td>H</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>V.H.C</td>
</tr>
<tr>
<td>Rule No. 7</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>H</td>
<td>V.H.C</td>
</tr>
<tr>
<td>Rule No. 8</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>V.H.C</td>
</tr>
<tr>
<td>Rule No. 9</td>
<td>L</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>V.H.C</td>
</tr>
</tbody>
</table>

Once all components are assessed according to the categories then only those components that have been identified as VHC and HC will be selected for AHP implementation where the behaviour of asset managers could be tracked whilst they make decisions about the most critical components of the asset.

5.5- SDMM Results
Once the most critical components are identified according to strategic fuzzy logic then the AHP will be used to identify the most appropriate maintenance strategy for critical components. One could argue that it would be easy to decide on a maintenance strategy once the criticality level is identified in which the most critical part requires techniques, such as DOM or CBM, and also for those components that have not been considered critical, i.e. FTM or RTF.

From an analysis of investigation reports, it is clear that there were many components within BP Texas City refinery that had been identified as being critical for implementing maintenance strategy like DOM and CBM. However, due to the inappropriate culture of asset management, no decision was actually made by the maintenance department on implementing the suggested maintenance strategy.
Therefore, in order to analyse the culture of asset management for BP Texas City refinery, the behaviour of asset management was modelled before and after failures. In fact two scenarios were defined whilst implementing AHP on the BP Texas City. The first scenario was before the failure when the culture of cost-cutting had been applied to the maintenance department and the second scenario was after the failure when the BP authorities considered safety as their first priority.

**Scenario 1: BP cost-cutting policy**

As stated earlier, in order to define a decision-making problem for AHP, a few steps need to be taken into account: defining the goal, assigning appropriate criteria to achieve the goal and identifying available alternatives.

In order to implement other steps, a particular component needs to be taken into account to show the relative importance of one criterion with respect to others. Based on the results obtained from strategic fuzzy logic, the blowdown drum was selected. Then, the judgement of the asset manager will be used to obtain a relative ranking of one criterion in relation to others.

However, instead of conducting an interview with the asset manager who was in charge of the whole asset, the decision that had been made towards asset management was used instead. According to the investigation report on the BP Texas City refinery explosion, the main concern of the asset manager was to reduce expenditure and save costs. Therefore, when the maintenance department prepared a business proposal to request a design out maintenance for the blowdown drum, the asset manager disagreed and stated that the ROI of such a maintenance strategy was not cost-effective and considered that a cost-cutting policy should be applied on maintenance. Therefore, such attitudes were used as inputs for AHP. Figure-61 presents the way these four different perspectives ranked with respect to each other.
As the main concern of the asset manager was to save costs, the relative importance of the financial perspective was much greater than any other perspective. Figure-61 illustrates the relative importance of the financial perspective versus customer perspective. In fact, these values outlined the culture of asset management before failure. Figure-62 and 63 prioritise the concerns of the asset manager with respect to four different perspectives whilst analysing the blowdown drum.
Figure 64-Priorities of different perspectives from the asset manager’s point of view

Once the relative importance of all criteria has been identified from the asset manager’s point of view, the relative importance of each criteria with respect to all alternatives then needs to be defined.

Figure-64 presents the results obtained according to assigned values i.e. the best alternative while giving too much emphasis of cost prioritised the maintenance strategy as FTM (planned preventive) as the best alternative and CBM as the less importance approach and DOM to be as the least important option whilst exactly the reverse prioritisation obtained while comparing the alternative with respect to safety.

Figure 65- AHP results for implementing maintenance strategy before failure

191
In fact, the safest option for blowdown drum was suggested to be design out maintenance but because the overall culture of asset management was cost-cutting, the overall results showed the best alternative to be planned preventive maintenance.

Figure-64 compares the relative importance of criteria and alternatives. The relative importance of criteria varies from high to low, i.e. financial, technical, and operational and safety perspective in that order.

Considering the financial perspective as the most important criteria meant that the most appropriate maintenance strategy was planned preventive, that is, fixed time maintenance as it is illustrated in Figure-65.

![Figure 66-Best maintenance strategy to be planned preventive maintenance for blowdown drum with culture of cost-cutting](image)

**Scenario 2: BP culture of safety as the first priority**

During the last decades, there have been many catastrophic incidents in the history of oil and gas such as the BP Texas City disaster and Deepwater Horizon. Since then, BP has decided to make safety its priority. Therefore, the revised judgement is based on this new culture.
Once the relative importance of one criterion with respect to others and all alternatives are revised based on the culture of safety as a first priority then the results obtained from AHP show how the priorities of maintenance strategy will be modified. Figure-67 shows that the best maintenance strategy for the blowdown drum is design out maintenance.
As can be seen in Figure-67, the best maintenance strategy for the blowdown drum is design out maintenance. It is important to note that AHP not only proposes the best maintenance alternative but also prioritises other maintenance alternatives.

**5.6-Conclusion**

Despite other researchers (Labib, 2004, Burhanuddin et al., 2011, Ishizaka and Nemery, 2014) that focused on operational and financial perspective of selecting critical equipment and implementing maintenance strategy, proposed strategic decision making model (SDMM) highlights the importance of criticality assessment method from a strategic perspective and suggest an approach to equipment criticality from more strategic perspective rather than operational perspective. This was done, by using artificial intelligence to improve the criticality assessment methods while combining the views of different managers. A systematic approach was used to apply fuzzy logic for decision making of selecting critical equipment.

The novelty of research is to propose an approach in which maintenance strategy can be applied based on the equipment criticality. The approach could have a significant impact on improving safety; reliability and operational availability while identifying heart of problem and ensuring the maintenance budget will be spend in the most critical part of an industrial asset.

It is important to mention that most of the assessment methods in actual practice compare the concerns of safety with cost. However, the proposed model establishes a strategy that enables a decision-maker to include both criteria in such a way that they do not contradict each other.

The SDMM suggests that existing criticality assessment methods for optimising maintenance delivery have limited value and are suffering from a lack of strategic
decision analysis. SDMM can be used to improve decision-making of criticality assessment methods and hence maintenance strategy implementation while addressing the safety on its own.

The analysis of different case studies were used to validate the usefulness of SDMM and also in-depth interviews with both academic and industrial experts have been used to confirm the appropriateness of SDMM in real practice. For instance one of the main comments was that SDMM need to look at the safety on its own. Such comments therefore implemented by creating specific category during rules generation of proposed strategic fuzzy logic model.

The results suggest that a strategic decision-making model could have significant impacts on improving safety, reliability and operational availability. This would enable asset managers to track the consequences of their decisions whilst dealing with criticality assessment approaches. SDMM could be also an effective tool in the hands of a maintenance department to convince their asset managers to make a maintenance investment.
CHAPTER 6: Discussion

6.1-Introduction
This chapter will discuss the current gaps in the decision-making phase of maintenance management and provide strong evidence to support the need to develop the SDMM. A large number of papers analysed to understand the strengths and weaknesses of the decision-making approaches in maintenance management therefore published papers are classified based on their contribution to different levels of decision making in maintenance management. The first section of this chapter addresses the issues proposed by the first hypothesis of this thesis:

Hypothesis 1: Maintenance management suffers from a lack of strategic decision analysis.

It then discussed how strategic decision-making model was developed to bridge this gap whilst analysing case studies and interviewing experts in the field. It also considers the findings of the SDMM with respect to the second and third hypothesis proposed in the introduction chapter:

Hypothesis 2: Existing methods of criticality assessment for optimising maintenance delivery have limited value.

Hypothesis 3: MCDM tools could be used to improve decision-making of criticality assessment methods and hence maintenance strategy implementation.

In addition, the validation of SDMM will be discussed in detail through the results obtained from in-depth interviews with both academic and industrial experts.
6.2- Discussion of finding for hypothesis 1

Limitation of decision analysis

Evidence 1- Maintenance models are oversimplified

Decision analysis in asset management has received much attention from academia during the last decades. (Dekker and Scarf, 1998) classified maintenance decision problems based on a timescale, discussing that maintenance should start at the early design stages of any system. This could strongly affect the maintainability of a system by considering appropriate accessibility, the level of redundancy and the type of equipment. (Dekker and Scarf, 1998) argued that the maintenance optimization model has been economically attractive. It was discussed that the optimisation model could effectively improve maintenance management.

There have been different models developed for assessing maintenance strategy. The majority of these have considered the concerns of production and maintenance managers (Labib, 2004) and also degradation and failure modelling (Van Noortwijk, 2009, Barata et al., 2002). It seems that some of these models are difficult for decision-makers to follow and some of them are far behind what is happening in reality due to unrealistic assumptions that make the models oversimplified. This highlights the need for the development of models that are capable of dealing with multi-criteria performance (Parida and Kumar, 2006), integration of human systems and organisational impacts in maintenance management (Léger et al., 2009).

The main concern with the performance indicator assessment is to identify criteria that can represent an aspect of reality or describe the condition of phenomena. Such criteria need to provide the right information to identify the potential improvement of asset management.
Therefore, it is necessary to develop appropriate models to evaluate the criteria introduced by KPI for maintenance. However, it seems that current models were developed for specific purposes and their effectiveness depends greatly on the skill of the modeller who codes the knowledge to resolve a specific problem. It takes a lot of effort and resources to adapt them for a different purpose (Clavareau and Labeau, 2009).

It is important to clarify at which level the maintenance decision needs to be taken. Traditionally, when a maintenance decision problem needed to be discussed, most people or staff simply thought in terms of MTTR, MTBF, the maintenance activity type and interval time, etc. These views are ones that can be described as being at an operational level. However, decision-making in maintenance should not be limited to the operational level. Despite many industrial plants experiencing catastrophic incidents, many companies too readily decide to deploy a cost-cutting policy towards the maintenance department without even evaluating the consequences of their decision. This occurred in the case of the refinery explosion in Texas City where the maintenance department had requested a budget of 2 million dollars to improve plant reliability but the board decided on cost-cutting instead (Steinzor and Havemann, 2011).

A catastrophic incident can destroy the reputation of a company and even disqualify it from continuing its business (Ray Sanchez, 2014). As such, it is no longer acceptable to consider a maintenance problem simply from an operational level; a strategic level must also be incorporated.

With this in mind, when a maintenance problem arises, it should not only be treated as a simple breakdown at the component level but consideration should be made of
the possible failure consequences in the unit, system and plant performance in terms of a strategic perspective. Such analysis could positively influence decision-making for maintenance at a strategic level where the maintenance budget would be allocated. In other words, it is essential to analyse a maintenance problem from an operational, tactical and strategic level. The combination of the views from these three levels could potentially improve the effectiveness and efficiency of decision-making in maintenance management. It is important to recognise all kinds of dependencies on the maintenance system at each level and its correlation to other levels. Decision-making at the strategic level needs to take all other levels into account but in practice it is very difficult to do so and it is mostly done in an inaccurate way.

In addition, it is worth mentioning that a system is a combination of machinery and humans who are supposed to fulfil a specific function. Machinery requires maintenance but the performance of humans also needs to be controlled and monitored which is a very difficult task. There is a degree of uncertainty involved because of the human function which will inevitably vary between industrial plants. The catastrophic incident on Three Mile Island (Rees, 2009) and the Piper Alpha (Flin, 2001) occurred largely as a results of human error.

Last but not least, some methods (Christer, 1999) deploy mathematical modelling which focuses on the optimum interval for preventing maintenance and inspection. Some have implemented statistical modelling (Barlow and Proschan, 1975) that applies quantitative approaches for prioritising maintenance activities and pinpointing critical equipment based on historic failure data (W.Labib, 2004). There could have been many other maintenance classifications in the literature. However, very few papers discussed maintenance management from a strategic perspective.
Evidence 2: Data collection and analysis V.S Decision analysis
In actual practice, computerised maintenance management systems (CMMS) packages have suffered from a serious limitation, which is a lack of decision analysis (Labib, 2008). This is because almost half of the time, money and effort were usually spent in collecting data and the remaining attempts were focused on data analysis, with almost 2.7% of CMMS effort used for decision analysis (Swanson, 1997).

![Lack of Decision Analysis]

Figure 69-Efforts at data collection, data analysis and decision analysis

Evidence 3- CMMS Features as Function of Price
The concern associated with a lack of decision analysis can be seen in the work of (Exton and Labib, 2002) where a missing link in CMMS packages was discussed in spare part decision analysis in which the features of CMMS’s function had been categorized with respect to different price packages which increased from data collocation to data analysis, network but did not provide any option for decision support (Labib and Exton, 2001).
Decision Support System (DSS)

It is important to discuss the concept of DSS whilst highlighting the lack of decision analysis in actual practice. DSS began in the early 1960s. A DSS is a computerised information system which enables decision-makers to enhance the quality of their decisions by providing easier access to the application of knowledge, statistical tools, information management systems, problem structure and problem recognition (Santana, 1995). It helps managers to interpret different alternatives according to the presented information.

DSS are capable of reducing maintenance costs by up to 30% after a specific period of time. It can improve the performance of preventive maintenance (PM) by eliminating the potential backlog. More interestingly, in the case of onshore and offshore operations, DSS recommends that operators should not to carry out PM even if there is a chance to do so. In other words, DSS is able to quantify the potential benefit that can be obtained from PM. However, data obtained from such systems does not seem to be accurate enough to draw statistically-valid conclusions (Dekker and van Rijn, 1996).

Operational Decision Support System (ODSS)

ODSS is designed to improve scheduling and planning by prioritising criteria and reducing the number of alternatives. It also reduces the workload for the annual
shutdown by allocating appropriate maintenance activities whilst there is an opportunity for maintenance. This could potentially impact on long-term strategies and rationalise the cost-effectiveness of maintenance. Moreover, it has a similar function to RCM, i.e. making these correlations are between the amount of maintenance work spent on the machine and the machine’s importance. However, one of its drawbacks is that it requires extensive data collection for specific activities.

The application of ODSS could be widely used in industry. The need to enhance the data analysis phase of maintenance management could potentially improve by using an ODSS. PROMPT is one such example which was developed for scheduling and planning for the maintenance of gas turbines onshore during its PM. This was described by (Dekker and van Rijn, 1996).

PROMPT consists of a multitude of tasks for PM, including adjustment and checking of instruments as well as replacement or repair of components like filters in a gas turbine. Most of these activities need to be executed during turbine shutdowns. Even though most turbines have an annual shutdown policy, these activities require multiple shutdowns for turbines which is not desirable in terms of operation. Opportunistic maintenance could occur during the maintenance of other parts of the plant like oil wells. However, these moments are hardly predictable as well as limited in terms of duration. Therefore, it is essential for prioritisation to have been evaluated for activities before the opportunity arises. In addition, maintenance management expect a cost benefit assessment of all PM intervals. ODSS was developed in order to deal with such problems. It is worth mentioning that, in order to overcome such problems, it is necessary to analyse problems from both an operational and a strategic point of view; the operational view should determine what
activity is required now and the strategic view must decide what frequency is best in the long-term (Yam et al., 2001).

Moreover, the implementation of AI can strengthen the robustness of ODSS. For instance, (Yam et al., 2001) deployed a neural network approach to detect equipment deterioration patterns with the aid of a proposed intelligent predictive decision support system (IPDSS) for condition based maintenance techniques. The model was tested in a power plant in which reliable fault diagnosis was recognised. In fact, such a result can be considered as an input for CMMS or any other maintenance management system that results in minimising the risk of catastrophic failure, cutting down unplanned forced outage and decreasing inventory costs for spare parts.

**ODSS vs SDSS**

ODSS aims to deal with activities associated with the operational phase, for instance planning and scheduling, in which the implementation of computer systems is required.

During the last couple of decades, most CMMS have provided information to users that they already know. It seems that such CMMS packages offer nothing more than a calendar task for maintenance activity when what is needed is a system that is capable of recognising choice between alternatives and answering what if questions. Therefore, ODSS was developed to fulfil such a demand. It is necessary for ODSS to communicate appropriately with the maintenance management information system to obtain the required information, i.e. time to failure distribution, MTTR, MTBF and many others. In other words, ideally the ODSS should function on top of maintenance management information systems. However, this is rarely the case in actual practice. It is worth mentioning that such information is mostly available in FMECA which needs to be considered as an input to CMMS. The combination of
using ODSS and CMMS would result in a better understanding of failure behaviour compared to the traditionally disorganised feedback about failures. However, such a combination is rare in industrial plants as different levels of the organisation seemingly speak in different languages.

The role of ODSS is to take into account all maintenance frequency and requirements, and plan the work that could be appropriately fitted into the production schedule. Therefore, the input data of ODSS can be best provided from CMMS. Such an attempt would be useful in an airline overhaul system.

SDSS focuses on problems at a higher level, i.e. the whole asset or unit, thus resulting in limited data necessary to consider in the DSS with much higher gains. Strategic decisions are more unstructured and could be different from one time to another. Therefore, it essentially requires a user-friendly interface and there is limited need for complicated databases in order to report information.

SDSS is capable of working independently so its development is much easier than ODSS where there is a need for training and for increasing the awareness of expertise in the field.

SDSS such as MAINOPT and KMOSS provide an opportunity to compare options and answer what if questions; such packages combine economic criteria and reliability concerns.

Even though companies like Shell use it and millions of dollars can be saved, one of its main drawbacks is the validity of input parameters. Inputs are assigned according to the judgements of engineers, i.e. instead of asking about Weibull shape parameters they ask about failure probability estimation.
Paper classification approach

The first hypothesis aimed to prove that there is currently a gap in maintenance and asset management. Hypothesis 1 is that: Maintenance management suffers from a lack of strategic decision analysis.

In order to address the issues proposed by the first hypothesis, it is important to discuss the SDMM and the contribution of papers on the decision-making phase of maintenance management.

As mentioned earlier, there are four dimensions proposed by (Kaplan and Norton, 2001) for strategic management: financial, customer, internal business perspective and learning and growth. In fact, these terms within the concept of maintenance management might refer to different terms. (Mather, 2005a) discussed the concepts of maintenance score cards in maintenance management and suggested 6 dimensions: environmental perspective, safety perspective, cost effectiveness perspective, productivity perspective, learning perspective and quality perspective. (Eti et al., 2006) suggest the existence of 5 dimensions to strategic maintenance management in Nigerian industries, namely management policy, support process, maintenance methodology, culture of organisation and work structuring.

Depending on the purpose of the research, these dimensions might be modified and also might be called different terms. As far as the purpose of SDMM is to identify the critical part of a plant and hence decide on maintenance strategy, similar to what was proposed in the concept of balance score card (BSC), there are four dimensions considered in the concept of maintenance management. Each of the published papers were classified based on their contributions to each of these dimensions, which are: technical perspective, operational perspective, financial perspective and safety perspective.
To be more specific, the papers were classified based on their contribution to the level of decision-making for maintenance management. For instance, a paper that considers factors such as maintenance cost and production loss cost in decision-making of maintenance strategy will be classified as a paper that contributes to the financial perspective and so on. Similarly, if the same paper includes safety and environmental issues when making decisions about maintenance strategy then it will be considered as a paper that contains both perspectives simultaneously as well as considering criteria like downtime, failure frequency and spare part management. Moreover, factors like pattern of failure, Weibull shape factor, the importance of a machine to the RBD, and functional and maintainability requirements represent the technical perspective.

Method used
In this research, a comprehensive literature review has been carried out in relation to maintenance management and its strategic dimensions. The literature research was carried out through electronic databases such as SpringerLink, InformaWorld, ScienceDirect, Emerald and many others. In total, 114 articles were reviewed and 58 were considered to be relevant to the current literature review.

A total of 14 journals related to maintenance management were reviewed during this research and 5 main journals were identified as most relevant to the purpose of the research. Figure-70 presents the methods used to identify the relevant papers in the literature.
Investigating contribution of published papers
The concept of BSC for strategic management was introduced by (Kaplan and Norton, 2001) who discussed how performance measures can be transferred to strategic management. Four perspectives were identified for strategic management: financial perspective, customer perspective, internal process perspective and learning and growth. The classification of papers was made based on their contribution to each of these four perspectives. In other words, the terms strategic maintenance and asset management require an investigation of the impact of maintenance activities in terms of commercial dimension, managerial dimension, technical dimension and operational dimension.
To be more specific, Kaplan and Norton argued that relying only on the financial measures in management systems is inadequate as financial measures reflect the results of previous performance. This in fact could damage the long-term value creation for the organisation. Therefore, the concept of a BSC was proposed to consider not only the financial measures but also more strategic measures that are essential for business success.

The reason why BSC is widely accepted by many companies is because of its ability to link measures with strategy and cause and effect linkages that suggest the hypotheses of the strategy. Moreover, BSC monitors the changing technology and its competitive advantages for the organisation. It was also discussed how it is possible to link measure and performance objectives with strategy by implementing BSC and a strategy map, and how a scorecard should be implemented in order to align the management system and process to the strategy.

In addition, it was argued that a strategy focused organisation must follow five main principles. First, it is essential to define the strategy in operational terms so it can be understood and translated from the operational perspective.

Second, even though different levels of the organisation use their own culture, language and bodies of knowledge, they all need to be aligned for a specific strategy. Third, it is well understood in many companies that senior managers and the CEO could not implement the strategy by themselves; everyone at every level of the organisation contributes to strategy implementation.

Fourth, most of the management process is centred around the budget and the operation of the plant whose performance will be measured against the plan periodically. However, apart from an annual strategic planning meeting, there are
few if any meetings held with senior managers to discuss the strategy periodically. Therefore, it is important to make the strategy a continual process within which there is an opportunity to test the strategy, get feedback and update the strategy based on the reports and available budget. The final principle is called ‘mobilize leadership for change’. This highlights the need for active involvement and ownership by the executive team in addition to the tools and processes introduced in the first four principles.

BSC introduces the idea that projects need to be considered as changeable processes rather than a matrix project. BSC initially concentrates on creating a momentum and mobilisation to enable the process to be launched. Once mobilised, the new performance model is installed and the management system changed.

The new management model evolves over several years, which means the new processes and cultural values will be formed into a new system for management which can be identified as a strategic management system.

**6.3-Analysis of results obtained from paper classification**

**Lack of strategic decision analysis**

There are two approaches to evaluate the existing gap in strategic decision analysis in maintenance and asset management: the academic approach and the industry-based one. Among the 114 papers reviewed only 58 papers contributed to the decision-making phase of maintenance management.

The following are the names of the top 5 journals and the number of papers published in each ones:

- Journal of Quality in Maintenance Engineering (27)
- Reliability Engineering & System Safety (14)
During the period of research (September 2012 to September 2015), the most popular journal in the field of maintenance was *Journal of Quality in Maintenance Engineering*.

**Financial Perspective**

In the classification of papers, the financial perspective in maintenance management refers to the research which proposed decision-making models associated with maintenance cost, spare part cost and production loss cost, etc. In fact, there are many models that tried to find the optimum balance between the financial perspective and safety perspective. It is important to note that a comparison of these two perspectives used to be the main element in making decisions on selecting critical components and hence maintenance strategy (Qi et al., 2015). Among 58
papers that contributed to decision-making in maintenance strategy, 34 papers considered the concern of cost as an input to their decision-making process.

**Safety Perspective**
The safety perspective in maintenance management refers to the research that discussed the concern of risk and safety whilst making decisions about maintenance strategy. In fact, the subjective judgements of decision-makers used to ascribe greater importance to safety than any other criteria. For instance, for a particular process plant the relative weight was given to safety four times more than to cost (Qi et al., 2015). Among 58 papers that contributed to decision-making in maintenance strategy, only 11 papers considered the concern of safety as an input to their decision-making process.

**Operational Perspective**
The operational perspective in maintenance management refers to the research that examined how to develop competencies, production scheduling, spare part inventory management, keeping updated with technology, and concerns about downtime and failure frequency. In fact, the operational perspective is the one which draws the great attention of researchers. Among the 58 papers that contributed to decision-making of maintenance strategy, 28 papers focused on the operational perspective for making decisions.

**Technical Perspective**
The technical perspective in maintenance management refers to the research that examined reliability techniques in order to understand how to select the optimum maintenance strategy, how to upgrade the design capabilities, etc. Unlike the safety perspective, there have been many papers published that consider the concerns of reliability in developing a decision-making model for maintenance strategy.
implementation. Among the 58 papers that contributed to the decision-making of maintenance strategy, 37 considered it from a technical perspective. In fact technical and financial perspectives are the ones which draw the most attention of researchers for developing maintenance management frameworks.

**Analysis of results**

It is important to note that most of the papers that was related with decision making of maintenance management considered only two perspectives at the same time. These are usually a combination of technical and financial perspectives and operational and financial perspectives.

This approach of classification enables the researcher to understand that most of the models developed in the literature discussed 2 dimensions and there were almost very few papers which considered the concerns of these four different perspectives simultaneously. It is worth mentioning that among this few papers only two papers had the applicative contribution. Figure-72 demonstrates the percentage of papers published w.r.t the number of dimensions contributed.

![Number of perspectives contributed with papers](image)

*Figure 72-The percentage of papers published w.r.t the number of dimensions contributed*
Much more importantly among the papers that contributed to the decision making of maintenance management; the safety perspective received least attention from the researcher whereas most of the researcher focused on the concerns of technical and operational perspectives. The Figure-73 demonstrated the efforts of researcher with respect to each of four these perspectives where the safety own only 10% of researcher’s efforts.

![Strategic Gap of Decision Analysis](image)

**Figure 73-The effort of research with respect to four perspectives**

Last but not least, the impacts of papers published were assessed by their contribution on different levels i.e. whether the contribution is theoretical, methodological or applicative. Where the theoretical refers to the papers that were just proposing a theoretical frameworks in maintenance management and methodological contribution refers to the papers that suggesting a methodology to improve decision making within maintenance management while the applicative contribution refers to the papers that not only proposed a methodology but also implemented the methodology in the industry and provided the results of the proposed frameworks. Figure-74 presents the percentage of papers published on these three levels.
There have been various models, frameworks, and approaches developed to improve decision-making phase of maintenance management in which most of these approaches failed to address the four dimensions of strategic management at the same time. Even though researches pay particular attention to financial and technical perspectives of maintenance management however the effect of safety had been eliminated in many of published papers and also even those models that address the concern of safety failed to look at the safety on its own rather providing a weighting scale for safety factor and simply add it up with some financial concerns such as production loss cost and maintenance cost (Qi et al., 2015). However maintenance models need to look at safety on its own rather than adding this factor with financial or any other concerns.

The comprehensive review of literature provides sufficient evidence that the maintenance models developed so far are suffering from a lack of strategic decision analysis and existing maintenance management models for optimising maintenance delivery have limited value. A guide for future research is to develop strategic decision making model by utilising multi criteria decision making (MCDM) tools while focusing on safety on its own and considering the effect of other perspectives.
6.4- Discussion of finding for hypothesis 2

Recall: Research questions & hypothesis
The second part of this chapter considers the existing gap in decision analysis in industrial plants. It will also discuss the approaches that have been developed to bridge this gap through case study analysis and in-depth interviews. It is now useful to recall the research questions that are associated with the second hypothesis.

5. What criticality assessment methods are used in the oil and gas sector for selecting critical parts of assets?

6. What are the strengths and weaknesses of current packages used for asset management?

7. Is there a gap in strategic decision analysis in such packages?

• How could criticality assessment methods be improved from a strategic perspective?

A range of information has been provided to answer the above questions in chapters 4 and 5 of this thesis. The discussion in this section will be based on the results obtained through in-depth interviews with experts. It is important to repeat the second hypothesis before discussing the findings of in-depth interviews.

Hypothesis 2: Existing criticality assessment methods for optimising maintenance delivery have limited value.

The Review of criticality assessment Methods
As discussed earlier, the purpose of criticality assessment methods is to provide a framework in which the maintenance strategy can be implemented accordingly. Thus, the content of a maintenance plan is highly dependent on what was suggested by the criticality assessment method.
The current practice of criticality assessment methods in many industrial plants such as refineries or oil production plants is to assess the process criticality for items and individual components from two perspectives. The first and the most important is to evaluate what if scenarios for each individual item to investigate its potential impact on the environment in terms of health and safety (Dekker et al., 1998). The second concern is to investigate the financial impact on the business in the case of a component or item failure (Lee and Hong, 2003).

There have been many benefits obtained through criticality assessment reviews in industrial plants. (Qi et al., 2015) stated that criticality assessment methods increase the level of safety and availability of equipment in terms of production which results in proper PM and lower maintenance costs. They also stated that the necessary information for maintenance activity can be gathered through the complete and accurate recording of maintenance activity and its cost. This provides necessary data with which maintenance managers can control and analyse the maintenance cost. Last but not least, it was argued that a criticality assessment review provides a great opportunity for scheduling, planning and forecasting whilst minimizing downtime.

The financial impact of implementing critical assessment methods has been discussed by (Afefy, 2010) who claimed that the proposed PM plan obtained from criticality assessment method saved 21.17% of annual costs for spare parts, reduced by 25.8% the total labour costs and also decreased the downtime cost associated with components by 80% for a particular process plant.

There have been similar approaches to criticality assessment which have discussed different aims and objectives for criticality assessment methods. Such criticality assessment methods may be used for other purposes, for instance reliability
engineering, risk management and maintenance management. Some of these techniques specifically focus on safety or risks whilst others focus on analysing the effects of failure in the production process.

However, the approaches used in industry have failed to address the four strategic perspectives simultaneously. The aim of the proposed SDMM is to tackle the current gap in such criticality assessment methods by combining the effects of these four perspectives whilst analysing the challenges for maintenance and asset managers through interview comments and case study analysis.

**Issues in current approach to criticality assessment methods**

The practice when following a criticality assessment method in many chemical plants, such as refineries and process plant divided into three main stages: the first is to review all piping and instrument diagrams (P&IDs) including equipment (rotating, fixed) down to the instrumental level; then, the specific scores are provided by experts to build a criticality matrix in which the criticality of equipment can be assessed; finally, appropriate suggestions are made for PM.

The assessment method initially investigates the primary function of an item. The consequence of functional failure for each item will be evaluated in terms of different criteria, for instance, the BP oil process plant used five criteria whilst the petrochemical plant used three criteria, i.e. safety, business impact and annual maintenance cost. The analysis of such consequences will usually be carried out by a team of experts who have the best knowledge of the plant in terms of maintenance/operation, production process and environmental concerns like discharge of content in waste water and air, etc.
Just before discussing the main challenges of criticality assessment methods, it is useful to outline once again the procedures of criticality assessment methods, in particular petrochemical plants, to highlight the associated issues and limitations.

Any decision-making problem has certain inputs and there are some rules which indicate certain outputs. In most industrial plants, the inputs for criticality assessment methods used to be in terms of safety and business impact and it was the same for this petrochemical plant. The combination of these two factors and annual maintenance costs was used to suggest the criticality level of components. It is important to note that different weightings will be provided for each criterion. For instance, this particular petrochemical plant considers the scale one for annual maintenance cost, scale four for safety and scale three for business impact. Which used a simple add up procedure to find out the criticality level of equipment using following formula:

\[
\text{OCL} = 4 \times \text{Safety Value} + 3 \times \text{Business Impact} + 1 \times \text{Annual Maintenance cost}
\]

(Qi et al., 2015)

The following concerns are the three main issues that are associated with most of the criticality assessment methods which require improvement.

- The first concern is related to the validity of values that are suggested for each input criterion. There are many items/equipment in assets on which different managers agree different numerical values but ultimately all experts have to agree on one number. However, such an approach for assigning numbers for each criterion could filter out important information. Therefore, there is a degree of uncertainty on each identified values, and so instead of having an exact number like 0 and 1, some values in between are required.
• The second concern is related to the output values that indicate the level of criticality, i.e. 0, 1, 2 as low, medium and high respectively. However, this means that many important criteria might not be taken into account, e.g. maintenance cost, pattern of failure, etc.

• Once the criticality level is identified for a specific item then a simple adding up approach used to consider the view of all three criteria simultaneously. The value of manual maintenance cost is usually assessed through an equation that gives different weighting for each criteria suggested by an expert multiplied by the value for each criteria. Therefore, the overall criticality has been calculated as:

\[ \text{OCL} = 4 \times \text{Safety Value} + 3 \times \text{Business Impact} + 1 \times \text{Annual Maintenance cost} \]

In this, the value of each criterion varies from 0-4. Therefore, the overall criticality number range is from 0-32.

One could argue that it would have been a great advantage if all criteria and weighting would have been considered once to rank the overall level of criticality. This means again that here the concern of safety and cost will just simply be added together with different weighting. However, according to the interview with Tom Lenahan it was argued that “safety needs to stand with its own and cost needs to stand with its own”. This approach is simply not acceptable as it makes a comparison between these two distinct criteria, cost and safety.

• The last concern is associated with the way rules are generated. The group of experts assigns rules for each combination. Even though the knowledge of experts is reliable for assigning such rules. However, it is not reasonable to neglect the uncertainties involved in the subjective judgement of humans.
Therefore, it is essential to analyse and fine-tune the rules to make them more appropriate in demonstrating the logic of the physical system.

More discussion has been present in section 6.6 while highlighting the interview results.

6.5- Discussion of finding for hypothesis 3

Recall: Aims and objective, research questions and hypothesis

Aims and Objectives:

- To propose a hybrid approach which combines AI techniques with MCDM tools to provide feedback for the decision-maker to understand how continues improvement can be achieved through the decision-making process.
- To propose a SDMM which enables decision-makers to make the most of tools, techniques and systems used, such as FMECA, RCM, QRA, CMMS, SAP, MAXIMO, etc to improve asset management.

Research Questions

- Is there any way to utilise AI techniques to select the most critical equipment in assets?
- What are the main criteria that are required to be considered for selecting the most critical item, component, unit or process in oil and gas industrial plants?
- How can MCDM tools be implemented to achieve continued improvement in maintenance management?

Hypothesis 3: MCDM tools could be used to improve decision-making of criticality assessment method and hence maintenance strategy implementation.
More importantly, the validation of SDMM will be discussed comprehensively through the results obtained from in-depth interviews with both academic and industrial experts.

**Discussion on the model proposed in COMADEM conference**

It is important to note that the model which proposed for maintenance strategy implementation in a BP oil process plant considered only the concern asset manager which was the starting point of developing a SDMM based on the feedbacks received from industrial experts attended in COMADEM. The following discussions stem from critical review of the paper.

It was discussing that the model proposed for CBM implementation adds to what is currently used with RCM. The concept and strategy was introduced in which the information of current RCM techniques can be used to reach a more effective conclusion.

The proposed model by Labib considers the implementation of maintenance strategy from operational level in which MTTR and MTBF have been considered as a basis of the decision. However, the contribution of the model proposed in COMADEM is to look at the maintenance management from more strategic level whilst considering the effect of two criteria, i.e. cost and safety. In fact DMG proposed a different maintenance strategy based on MTTR and MTBF, whereas the proposed model identifies the criticality of machinery for CBM consideration based on cost and safety. In fact, these are the criteria that have not been addressed in the DMG.

It was discussed that there is a gap in research for strategic decision analysis in maintenance strategy implementation because the models like DMG ignore the effects of safety. Ignoring the effects of safety in industries like oil and gas could
potentially destroy the reputation of a company. For example, BP was banned from continuing its operation in the Gulf of Mexico. Also, the possible costs of failure consequences were eliminated as these are difficult to estimate.

The paper discusses the current gaps in decision-making about critical equipment in real practice. Discussion on decision-making for CBM should not only be limited to the operational level as the criticality of CBM implementation for each machine might vary with respect to the concerns of top level managers. This model indicates that DMG might be appropriate for the manufacturing industry but the implementation of such a model might be challenging in the oil and gas industry.

The findings of the paper can be considered as follows:

- Introduce a culture for asset management that highlights the need to look at the CBM implementation not only from an operational level but also a strategic level.
- Demonstrate how fuzzy logic can be applied to CBM. The research demonstrates the effectiveness of fuzzy logic for CBM implementation from a strategic level.
- Propose a decision-making framework. The research demonstrates that the application of AHP combined with fuzzy logic provides a decision-making framework.

The case study was used to identify the existing gap in decision analysis in real practice i.e. the simple add up procedure was used for selecting critical equipment and hence to decide on CBM. The approach used locally seems to ignore the costs of unforeseen failure and its consequential production losses. The following are some more recommendations:
Basically, it is necessary to conduct in-depth interviews with top level management. The semi-structured interview would provide the necessary information to consider maintenance strategy implementation from a strategic level. Then, based on the data gathered the two stage model could be restructured according to the requirements of industry and plant specification. It was also argued that safety and cost are important criteria but not enough. Such questions were the main motivations for developing a multi-dimensional maintenance model. These feedbacks have been taken on board and critical modifications have been made whilst developing SDMM.

**SDMM development Process**

The need to develop a SDMM became clear when the gaps of decision analysis in selecting critical components and deciding on a maintenance strategy were identified during analysis of the BP case study whilst developing a maintenance model for CBM implementation and getting feedback during its development.

It is worth mentioning that the maintenance model was developed during the time that the author was aiming to introduce an approach to achieve continued improvement in the oil and gas project. Therefore during this PhD, training courses were attended in order to gain a deeper understanding of the relevant subjects:

1. Training course in Reliability and Assessed Management; this included the concept of reliability assessment, reliability analysis, FMECA, FTA, RBD and Weibull analysis. This was taught by John Harris.
2. Training course in Decision-Making for Maintenance Management taught by Prof Ashraf Labib. The author enhanced his knowledge about decision-making tools and techniques, such as AHP and fuzzy logic. The author also attended a master class in AI in Portsmouth Business School where he learned how AI can be utilised in the decision-making process.
3. Training course in Maintenance Strategy taught by Paul Wheelhouse. The author learnt about the functions of different maintenance strategies and got involved in a workshop where the BP oil refinery plant was analysed in terms of its criticality assessment method implemented for CBM selection. It was here that the gap in research was identified, i.e. the lack of a strategic decision analysis for selecting a maintenance strategy.

As discussed earlier, the criticality assessment method in the BP process plant used to be evaluated by adding up the numbers given by staff working at the plant for each criterion. For example, staff working on the asset agreed to give a number between 1 to 5 for operational reliability, safety, cost, etc and those machines that received the highest values were considered as the most critical components. Roughly the same approach has been followed in many other industrial plants. Therefore, SDMM has been developed to address the gap of decision analysis in maintenance management. It considers not only the simple adding up procedures but suggested an approach to analyse each criterion in its own right by applying fuzzy logic and AHP.

The first part of the model focuses on identifying the most critical part of the plant by combining the views of safety, risk, production, maintenance, and reliability and finance managers. As the Pareto analysis suggests, 80% of problems come from 20% of machinery. As such, SDMM has been developed to identify the most problematic machinery that can be considered to be at the heart of the problem within an industrial asset. This ensures that the budget is invested in the right place. The second part focuses on prioritising maintenance strategy whilst considering the culture of asset management.
SDMM has improved the current criticality assessment method in the oil and gas industry by utilising AI techniques. In fact, SDMM is a tool in the hands of the maintenance department to convince the decision-makers to improve their culture of asset management through continued improvement and learning from failures.

6.6- Discussion with expert: SDMM strengths and weaknesses

Academic and industrial experts
The interviews were conducted with both academic and industrial experts. The main academic interviewee was Professor Ashraf Labib who is an expert in decision-making and asset management. Ashraf Labib is a Professor of Operations and Decision Analysis and is currently the Associate Dean for Research and has been the Director of the DBA Programme at Portsmouth Business School (PBS).

Most of the interviewees were based in industry; for instance Dr Joe Barnes is a maintenance leader for Shell. Dr Barnes is currently working on the Brent Charlie production improvement project.

Mr Tom Lenahan is a director at TLL Ltd. He has worked as an independent consultant assisting clients to achieve cost-effective solutions to difficult issues in maintenance strategy in general and turnaround management in particular.

Moreover Mr Paul Wheelhouse is the Chairman of Red Wheel Solutions Ltd. He has worked in the speciality chemicals business for 20 years in a variety of engineering, production and distribution roles at several locations in Europe. A large part of his time has been devoted to improving the performance of plants, work processes and the functioning of groups. For the past fifteen years, Paul has been engaged in asset management consulting. Similarly Mr John Harris has been getting involved on reliability practices for more than 30 years.
There were other interviews with people who have been working in different industries and came to attend the maintenance and asset management course at the University of Manchester, namely an Italian predictive maintenance planner for offshore assets, a senior maintenance manager at the Ministry of Defence in Oman and a maintenance practitioner in the oil and gas industry from Denmark. In total, 12 interviews were conducted. Due to confidentiality of companies the many details of interviews were not included in the text of this thesis however the transcript of few interviews included in the Appendix B.

These interviews helped the author to modify, develop and validate the proposed SDMM. The following section presents the discussions on the strengths and weaknesses of the proposed model. The main focus is on highlighting the most relevant interviews that contributed to the development of SDMM. To see more questions and answers during each interview see Appendix B. The following discussions have been classified based on the following three themes.

**Theme 1- Lack of strategic decision analysis**

**Theme 2-Limited values of maintenance strategy approaches**

**Theme 3- MCDM tools could be incorporate for improve decision making**

**Interview Results with Industrial Experts**

**The first interview with Mr. Tom Lenahan**

**Theme 1- Lack of strategic decision analysis**

*Questions*: “I would like to validate the criteria that have been taken into account to my model from your perspective as you have been working in the oil and gas industry for more 30 years”

*Tom*: “One of the things that you mentioned is to look at the problem from strategic angel, then it must be an investment for it and it cost. I mean cost is the money that we need to spend in some way, but investment is the money that we invest in order to earn more money, and one of the questions that you asked was, it is possible to make an investment in maintenance? My answer would be yes, because if you invest in reliability of plant it means that you are investing in the life of the asset, but
unfortunately I think in most companies still the main concern is cost, which is led to the cost cutting culture. There one thing puzzles me, I wonder if the senior management of companies really understand what maintenance is, you know, what are the parameters, and what it actually can do, what would be the consequences if you do not carry out maintenance properly.”

**Theme 2-Limited values of implementing maintenance strategy**

**Questions:** Do you know any company that looks at the maintenance as a strategic perspective?

Tom: “Not really, I think there is big misunderstanding what maintenance is really, in some cases if you cost cut to save, the benefit for immediate, for example if you reduce $10 million to $8 million, so you saved $2 million, so the people in who are responsible for maintenance tell the senior management that there would be consequences which could be medium or long term, so if you cut the maintenance budget with $2 million, the plant might shutdown in two years, which is a problem, the people cut the maintenance budget do not care about what you are talking about, it is fortune because the benefit is immediate but the consequences is the longer term, but the consequence when they happened, they have many, many, many times over impact”

The Second Interview with Mr. Tom Lenahan

**Theme3- MCDM tools could be incorporate for improve decision making**

**Questions:** I used MCDM tools to improve criticality assessment methods and hence implementing maintenance strategy, do you think about using MCDM in such decision making problems?

Tom: when you look at the criticality safety, it is on its own, anything else depending on safety and so if you look at on the most criticality hierarchy, the top level is safety, and then we don’t want the equipment to fails but if it fails would it have any consequences, the next level normally is operation, what effect does it have on production. Will it stop or interrupt or reduce production, etc. Umm the next level down is how all these thing affect each other, any direct or indirect cost. So in the criticality hierarchy is top level is safety, then production and then cost and lastly technical. Today there is one thing that is safety need to be in the first priorities. I am wondering how your model deal with this concern?

**Answer:** Basically, this is the reason why I decided to applied fuzzy logic, because I do not feel we can optimize something with safety and cost to make comparison between safety and cost where you ended up with finding a trade-off between cost and safety. But with using fuzzy logic the specific rules have been allocated to eliminate such concern. And of the safety is reaching to its limit the outcome of the
strategic fuzzy model give the highest criticality to that specific unit regardless of the importance of other criteria.

Tom: yes, I understand, so if you take another case if the safety is low but the reliability was high and cost is high would that then considered to be high critical?

Answer: Well, it depends, this could be the asset manager or expert judgment, but for the initial stage I develop the rules for oil and gas plants. It is how we quantify the qualitative data. Like that numerical judgments will be transfer to the fuzzy logic and AHP to be use as based of precise decisions. The advance phase of model would be when you work on how the system generates rules in itself in which it could be a PhD in its own.

The interview with Prof Ashraf Labib
During development of SDMM the in-depth interview carried out with Prof Ashraf Labib. The in-depth interview was designed to discuss the usefulness of SDMM in order to select critical equipment in the oil and gas industry that is upstream and downstream projects. It was discussed that there are two phases of research; phase one focuses on shortlisting the critical parts, phase two selects the maintenance strategy. Short-term validation and long term validation were also discussed by considering how to learn from failures and the industrial implementation of SDMM.

The following are the highlights of the interviews with Ashraf Labib:

Theme 1- Lack of strategic decision analysis
The researcher start to explained about BP oil production platform where they management team decided to use all installed redundant parts in the main production which the production rate increase to more than 150% but the asset face to many breakdown for small, medium and high rotating equipments and therefore management decided to identify the most critical components for CBM implementation. There are four criteria considered in the criticality assessment
method i.e. operating point, cost, safety and operational reliability. Consequently the developed SDMM presented in order to get the feedback.

**Pro. Ashraf Labib:** What is interesting in you model is that you have both safety and cost, you could different strategy for different combinations. Because in decision making Grid we only look at frequency and downtime, but here you look at the safety as dimension, which is very interesting, and you have some sort of strategy for each type of combination. Here you have safety dimension which is very interesting dimension to your model. So you can have some sort of strategies depending on the safety. For example here what sort of strategy we can apply high and low, high and high which is CBM. That is very interesting Very good.

**Researcher:** In my research I highlighted that maintenance objectives are not meeting organizational objectives.

**Pro Ashraf Labib:** yes that is really true, there is need to align maintenance department objective with organizational objectives.

**Researcher:** To make the importance of the models more clearer I would like to explain the BP conflict when Tony Hayward became a chief executive of company in 2007 and emphasised that we put the safety in the first priority however the BP was experiencing catastrophic indecent like Deepwater horizon oil spill, Texas city and other explosion. Such experiences in fact confirmed that the safety was not in first priority in the real practice of the cultural or organisation.

With the aid of SDMM the maintenance department provides the list of most importance parts for implementing maintenance strategies and therefore depending on the concern of asset manager appropriate maintenance strategy can be implemented. SDMM provides an opportunity to track the consequence of decision made with asset manager towards maintenance management. In which it give the feedbacks to asset managers every quarterly to increase their awareness about the consequences of their decisions. And that feedbacks provide a learning and growth for the asset and it is way towards continues improvement.

**Theme 2-Limited values of maintenance strategy approaches**

**Researcher:** In our model, AHP used only for the component that have been selected as being the most critical part, So AHP goal is to select the most appropriate maintenance strategy for the most critical component, there are 4 criteria and there are three alternative maintenance strategy i.e. Fix time maintenance, condition based monitoring and design out maintenance. There could be and skill level upgraded strategy be updated into model. However, for the critical part of the plant run to failure (RTF) strategy is not acceptable at all because nobody wants to have failure for the most critical component of the asset. This is where we get engaged the senior manager on decision making process, and let them know what would be there consequences of their decision making.
**Pro Ashraf Labib:** It is very good model, you are using hybrid methods i.e. AHP and Fuzzy logic which is very good, you know on the paper that I wrote that I used Fuzzy and AHP for selecting Maintenance strategy. But my model was much less in terms of scale which not included risk, safety which you included and also I like here that you would like to applied the model in some applications in industry. It would be nice to show to industry, and investigate how this can be demonstrated in industry. How this process can be shown to the industry.

**Theme 3- MCDM tools could be incorporate for improve decision making**

**Pro Ashraf Labib:** Is it possible to show me the fuzzy logic rule evaluation phase? I am trying to understand why you used Fuzzy logic but not AHP to priorities criticality. Why Fuzzy Logic used? As challenge why you did used Fuzzy Logic not AHP?

**Researcher:** One of the concerns that I had with AHP was that each components requires lots of pairwise comparison for each component i.e. increasing number subjective judgments which improve the degree of uncertainties. And this is one of the reasons I was thinking to reduce the number of judgment and uncertainties while applying fuzzy logic and then apply AHP in the second part of the model.

**Pro Ashraf Labib:** your answer is adequate but for me to appreciate the use of fuzzy logic, do you expect every decision maker to contribute to fuzzy logic, in which way, for example in the rules or? How would be their contribution?

**Researcher:** I used a trapezoidal membership functions.

**Pro Ashraf Labib:** right, what you did is correct, because some people use triangular, but it need to have shoulder as you did. It is simplistic way when you use the trapezoidal shapes as what you did here in the model, and to the fuzziness it is important to highlight what is the shape of membership functions. This why you are using Fuzzy logic Not AHP, because in AHP you can have the same columns of you input to model and each of these columns could be an criteria, here you assuming the scoring high on RBD, or high in MTBF, or high in Safety, or high in Cost will give you Very Highly Critical (VHC). But there is implicit assumption, here you making is that each of these criteria is equality weighted. It means that you consider Cost is equal to Safety, is equal to MTTR and is equal MTBF.

**Researcher:** Basically, we have got a list of component and applied fuzzy logic to assess criticality of components from A to Z, Some of the inputs are quantitative for instance MTTR and MTBF, and also from risk perspective there are methods like QRA, FTA, RBD, etc which are quantitative analysis that can be consider as input to the model. But there are some curtain inputs that might require qualitative judgement.
of decision maker like importance of machine with respect to RBD of asset and safety.

**Pro Ashraf Labib:** Your model looks perfect, but still I have a bit concern about assuming they are all equally weighted because if I am decision maker specially in safety, and look at your model and see that you consider safety equal cost or something else it would not be acceptable. Safety for some people is very important.

**Researcher:** Yes you are right, but this concern has been address during fuzzy rule evaluation. In fact my model is criticizing the weight approach to criteria such as safety and cost, in fact the model deal with these concern while defining rules for strategic fuzzy logic and depending on what is needed for each plant the importance of one manager can be define to be more than others such as safety. I argued that it is not simply truth to just assign weights for criteria such as safety and finalise decision based on the ranking obtained. If someone say weighing of safety should be 5 time than cost, one could argue why not 4 times than cost and these subjective judgement will produce different results. However by allocating relative rules in fuzzy logic if the concern of safety was very high the result would be very high irrespective of other criteria and so on. However it is important to note the weighting for different perspective has been considered in AHP where the behaviour of asset manager can be identified while giving the weights for different perspectives that address the concern of cost, safety and many other factors.
6.7- Conclusion
It is important to revisit the main aims and objective of this research, which end up to three hypotheses. The figure-75 present how the main aims and objective address through each research questions.

Figure 75-The alignment of aims and objectives with research questions
The first part of this chapter discussed the current gaps in the decision-making phase of maintenance management and proved that there is a need to develop a SDMM. A large number of papers were analysed to understand the strengths and weaknesses of the decision-making approaches in maintenance management that they describe. The validity of the first hypothesis of the thesis “Maintenance management suffers from a lack of strategic decision analysis”, also discussed.

The second part of this chapter critically discussed the process in which SDMM was developed to bridge this gap whilst analysing interviews conducted with experts in the field. It also provided evidence that SDMM will address the concerns proposed by the second and third hypotheses:

Hypothesis 2: *Existing methods of criticality assessment for optimising maintenance delivery have limited value.*

Hypothesis 3: *MCDM tools could be used to improve decision-making of criticality assessment method and hence maintenance strategy implementation.*

More importantly, the usefulness of SDMM has been discussed through the results obtained from in-depth interviews with both academics and industrial experts.
CHAPTER 7: Conclusion

7.1-Summary of Chapters
The first chapter of thesis provided a general background on maintenance strategy implementation and highlight the prior works that developed a decision making model for maintenance strategy which followed by introducing the problem statement to the research. Consequently the aims and objectives of research have been discussed and accordingly the research questions that address the aims and objective of research are designed and the relative hypotheses are introduced.

The second chapter discussed the concept of reliability, availability and maintenance followed by a review of the techniques used for maintenance management. It then continues by identifying the gaps of literature of the decision-making phase of maintenance and asset management which address the first hypothesis i.e. lack of strategic decision analysis.

The third chapter of the thesis presented available research methodology in management science and discussed the reason of the research methodology that selected for the current study. Both primary and secondly data collection processes are discussed comprehensively. The reason of using fuzzy logic and AHP has been presented through the series of questions.

The fourth chapter analysed the 4 case studies in which the first three case studies were addressing the second hypothesis where the sufficient evidences provided to highlight that criticality assessment method used in industry have limited values and the last case study was used to demonstrate MCDM tools could be incorporate to improve decision making of criticality assessment method and hence maintenance strategy implementation. In which such case study analysis was led to development of the SDMM.
The fifth chapter of thesis discussed the development process of SDMM in detail in which its development process is explained through both case study analysis and interview results and then a justification is provided for the use of fuzzy logic and AHP.

The chapter 6 discussed the research outputs through the findings of literature review, case study analysis and interview results. The chapter is divided into two parts. The first part highlights the contribution of this research by identifying the current gap in the literature where large number of papers were analysed and criticised based on their weaknesses and strengths in decision-making for implementing maintenance strategies. Total number of 114 papers reviewed in which 58 papers were classified in terms of their contribution to different levels of maintenance and asset management. More importantly the second part of this chapter critically reviewed the SDMM based on the interviews results. The validity of the model is examined through the feedbacks provided with experts in the field of asset and maintenance management both from academia and industry in which the recommendations for future research have been given.

7.2- Contribution to knowledge
There has been a wealth of research that investigates the cause and effects of criticality assessment methods for implementing maintenance strategies but there are still many concerns with such decision-making processes as they suffer from a lack of decision analysis. The main challenge perceived is the inability to make decisions in selecting critical equipment from a strategic perspective and hence deciding on maintenance strategies.

Due to the complex nature of such decision-making, many models have been developed in the literature to address this gap by focusing on operational concerns,
such as those of maintenance and production managers. However, many of these models ignore the effects of strategic concerns, for example, safety, risk, and tightly-controlled operational expenditure limits. However, little research has been published that links the strategic dimensions of maintenance and asset management simultaneously whilst proposing a theoretical framework rather than applicative models.

The contribution to the knowledge builds upon earlier works on decision-making for selecting critical equipment and maintenance strategy. It sets out to construct three hypotheses by introducing evidence from a comprehensive literature review, case study analysis and in-depth interviews.

The thesis focuses on artificial intelligence and multi-criteria decision-making techniques (i.e. fuzzy logic and Analytical Hierarchy Process) to bridge this gap. It proposes a strategic decision-making model in maintenance and asset management for selecting critical equipment and deciding on a maintenance strategy.

The research output suggests that existing criticality assessment methods for optimising maintenance delivery have limited value and are suffering from a lack of strategic decision analysis. Multi-criteria decision-making tools could be used to improve decision-making of criticality assessment methods and hence maintenance strategy implementation.

The validity of the proposed strategic decision-making model was tested through case study analysis and in-depth interviews. The results suggest that a strategic decision-making model could have a significant impact on improving safety, reliability and operational availability. This would enable asset managers to track the consequences of their decisions whilst dealing with maintenance. A strategic
decision-making model is also an effective tool in the hands of a maintenance department to convince their asset managers to make a maintenance investment.

7.3- Research Limitations
The limitations of the research were discussed briefly in the introduction chapter. That section focused on the barriers that reduced the quality of research in terms of industrial implementation that could be addressed in further research. The main restriction was that it was very difficult to access real data from oil and gas industrial assets to run the proposed SDMM.

Therefore, the model was validated mainly through in-depth interviews with managers of oil and gas consulting companies who are very familiar with the concerns of asset managers and also with the qualitative feedback of experts in the field of maintenance management. Experts from different types of organisations were interviewed. It should be noted that their views may differ slightly from the views of asset managers in industrial plants.

Case study analysis was also used to validate the usefulness of SDMM, with the historic failure data having been gathered from investigation reports of recent failures in the oil and gas industry. However, due to confidentiality limited data were presented in such reports –hypothetical scenarios were used to present how the model works in general.

Last but not least, because the strategic concept is long term in its nature, a long period of time is required to analyse the performance of SDMM across industry. This is almost impossible within a PhD timeframe.
7.4-A guide for further research
SDMM is a methodological approach to maintenance and asset management. It was initially developed based on case study analysis and was created through interviews with experts in the oil and gas sector. It provides the basic needs of such industrial assets. In fact, the whole method attempts to systematise the decision-making process and model the complexity of selecting critical components which is a concern with maintenance strategy implementation. However, this does not mean that the effect of other issues for other industries has been ignored. Whatever was proposed in this research is the beginning of such a process in terms of identifying an approach to deal with criticality assessment methods and maintenance strategy implementation; it is not the end result of the implementation of a strategy.

It is important to mention that the proposed SDMM is sufficiently general to allow the incorporation of a range of important objectives, asset managers and essential criteria. It is also specific enough in that it can help decision-makers to collect the required data as input for the model and modify the rules depending on their needs, the specific business context or environmental concerns. It was acknowledged that industrial application of the proposed SDMM within a different range of industrial assets needs to be further investigated in future research; therefore, the industrial proposal has been prepared accordingly.

For industrial implementation, it is first necessary to investigate what type of machines exist in an asset, which of them are considered to be critical and what maintenance strategy has already been taken towards each individual component within the current practice of organisations. Consequently, the SDMM needs to be implemented to assess the criticality of equipment from a strategic perspective and make suggestions about what can be offered by SDMM. It is important to discuss
how SDMM would offer better results than what already exists, or how an asset manager would know that SDMM works better. This can be achieved through roundtable discussions with managers, supervisors and experts who are working in the plant and are familiar with the machine that gives the output along with the results obtained from the model and then comparing it with what they are doing.

Basically, each industrial plant has its own criticality assessment method that it uses to find the most critical components, and the maintenance strategies are known for the critical components. The first phase of SDMM can be implemented to distinguish the differences between the selected components as the most critical parts of the plant with what has been proposed by SDMM to improve asset management from a strategic perspective. There are two possible outcomes of such analysis. The first is that similar results of equipment criticality will be achieved through SDMM which confirm the robustness of the first phase of the model. Even if the same result is achieved with what they are doing in actual practice, the model can be verified by what they are doing and then more discussions can suggest advantages of the model such as being less time and cost consuming, being user-friendly for implementation etc. The second outcome is if different results are obtained from SDMM. In such a case, discussion and research should be carried out to see if either approach has ignored the effect of some criteria and what methods have been considered to combine the effect of all criteria in the overall criticality level of equipment.

These discussions can enhance capabilities of both methods (traditional practice on assets and SDMM) and provide an opportunity for them to learn from each other in terms of identifying the most critical components.
The second phase of the model was developed to analyze the organizational behaviour of asset managers. It provides a tool with which the decision-maker can understand the consequences of their decisions. With SDMM, the asset manager is asked to give relative importance to individual criterion in relation to each other. This results in the best maintenance strategy based on the attitude of the asset manager. The asset manager might accept the proposed maintenance strategy of SDMM or he might not want to invest in such a maintenance strategy, and so the consequence of his decision can be tracked by the model.

With the aid of SDMM, the maintenance department can propose parts of a plant that need most attention, the asset manager can propose maintenance strategies, and with the aid of sensitivity analysis senior managers can be provided with feedback every quarter to increase their awareness about the consequences of their decisions. Such feedback provides information and allows the asset to be developed. The growth of the asset is a way to continue improving it.

For this reason, industrial application of the proposed SDMM within different ranges of industrial assets needs to be further investigated in future research.

7.5-Industrial Proposal
There are two main stages in conducting SDMM in industry. The first is SDMM equipment selection (effectiveness) followed by focused action (efficiency) where SDMM indicates the best trade-off based on a decision made towards asset management.

SDMM is an innovative approach which offers a decision map according to the collected data to suggest the appropriate maintenance strategies. To be specific, SDMM acts as a map to indicate the performance of the worst machines based on
multiple criteria using fuzzy logic analysis. The objective is to deploy appropriate maintenance strategies to improve overall reliability, i.e. the development of machines towards an improved state with regard to multiple criteria. The outcome of the model is a standardised maintenance strategy that can be implemented in the industrial plant to improve the overall reliability of the plant and reduce the risk of failure in the most logical way that prioritizes the proposed actions.

Depending on the availability of the data in an industrial plant, whether the Computerized Maintenance Management System (CMMS) is running or not, there are a series of data that need to be collected, such as asset register, i.e. machine identifier; counter of faults, i.e. frequency; timer of faults, i.e. down-time; and the level of faults i.e. hierarchical. These will be discussed in more detail in the following section.

**Data for technical perspective**
There have been 8 criteria considered as inputs to SDMM which includes both qualitative and quantitative data. In order to gather the required data for evaluating equipment criticality from a technical perspective, it is necessary to extract reliability information from any CMMS packages used in the plant.

The first criterion is to understand the nature of equipment failure. In fact, some techniques have been developed to investigate the patterns of failure, such as Weibull analysis. The output Weibull analysis indicates whether the associated failures with equipment are infant, random or wear out. For plants that do not use Weibull analysis, the knowledge of reliability managers or other experts who have in-depth understanding of equipment behaviour and/or historical failure data could be utilised to gather the necessary information instead. The second criterion considered is the importance of the machine within the RBD of the plant. The
knowledge of the process engineer and maintenance and operational supervisors would be useful to investigate the importance of a machine with respect to the whole function of the plant.

It necessary to understand whether the failure of the component affects only its own function or if it could cause a system to stop working and/or it could result in downtime of a plant. Here, the advantages of techniques such as FMEA, FTA and RBD might receive greater attention from an expert in a plant.

Moreover the component can be categories in different group with respect to the availability of redundant parts and its function with respect to production.

**Data for operational perspective**
In order to gather the required data for evaluating equipment criticality from an operational perspective, it is necessary to extract the relative information from any CMMS packages which represent the concerns of production and maintenance managers, i.e. downtime and failure frequency. If there is no computerised maintenance management system within a plant, such information might be available in historic failure data gathered manually. These two factors can best be described as MTBF and MTTR.

**Data for safety perspective**
There have been many approaches implemented in industry to consider the effect of safety while making decision for maintenance investment. One of the best-known methods is the quantitative risk assessment approach which has two main inputs: likelihood of failure and consequence of failure. One of the main shortcomings of such an approach is that it provides a long list of items considered critical for investment. In other words, in each plant there are many types of equipment that
have a very low likelihood of failure but if one of these fails it will cause a big
downtime and a catastrophic incident.

These two dimensions, i.e. likelihood and consequence of failure, have been
considered as an input to assess the criticality of components with respect to risk and
safety. In fact, the implementation of fuzzy logic could effectively contribute to
reducing the degree of uncertainty in such a QRA technique.

It is important to mention that almost all criticality assessment methods in actual
practice compare the concerns of safety with cost. However, the proposed model
establishes a strategy that enables a decision-maker to include both criteria in such a
way that they do not contradict each other.

Data for financial perspective
In order to deal with concern of senior managers there are two dimensions need to
consider as inputs to SDMM i.e. the cost of maintenance per year and the production
cost loss in the case of failure. In fact cost of maintenance per year for each
components can be extracted from CMMS but the cost of production loss might
require more detail calculation using expert judgement though roundtable discussion.
One could argued that there are many essential element associated with financial
concern that SDMM has not taken into account such as the potential cost loss of
environmental damages, losing reputation i.e. BP performance in gulf of Mexico and
many others. Such criticisms are well appreciated however this is the assumption
made during PhD timeframe and as it was discussed earlier SDMM proposing a
framework which is flexible model that can be adjusted depending on the request of
industrial plant but one should be aware as the number of inputs increase the way
rules need to be assigned get more complicated and it might introduce a degree of
uncertainly to the end results. The following will explain future information with respect to SDMM industrial implementation.

Once the criticality of equipment has been identified then the AHP can be implemented to simulate the behaviour of humans towards maintenance and asset management. Only equipment that has been defined as very highly critical or highly critical will be considered for AHP implementation.

Even though there are techniques that suggest CBM or DOM maintenance strategy based for critical equipment, but it does not mean that such suggestions for maintenance strategies have actually been implemented during for critical equipment. Organisational culture plays an important role for which could results in different strategy implementation in fact such attitudes have been observed in many industrial plants that have experienced catastrophic incidents such as BP Texas City where the culture of the organisation affected maintenance management.

As far as the AHP suggest the maintenance strategy for critical machines therefore there are 3 maintenance strategies suggested by SDMM i.e. Condition Based Monitoring (CBM), Fixed Time Maintenance (FTM) and lastly Design Out Maintenance (DOM) in which the aim is to conduct the best strategies to move towards continues improvement.

The initial data will be converted to the excel format suitable for entry into the SDMM method, where the SDMM suggests the most critical components and compare with the existing methods to improve the reliability of the plants. Accordingly recommendation will be considered based on calculation and consideration of the fuzzy decision that deployed with SDMM. Then the organisational behaviour and the culture of decision maker will be assess with second phase of SDMM where AHP and suggest the best maintenance strategy. For
future research the extension of SDMM model can be introduced as the third phase of SDMM where the model focuses on resource allocation. And propose the best trade-off in terms of cost and benefits in terms of availability of financial resources.
7.6-Publications and academic attempts

Papers under Publication


- M. Moghaddaszadeh Kermani, Moray W. Kidd “Future perspectives on Strategic Maintenance & Asset Management: Directions for future research” Journal of Quality and Reliability management, Submitted 28 August 2015

ACCEPTED PAPERS

- M. Moghaddaszadeh Kermani, Moray W. Kidd “A Decision Making Framework for Maintenance Strategy” 27th International Congress of Condition Monitoring and Diagnostic and Engineering (COMADEM) Brisbane Australia (September 16-18, 2014)

- M. Moghaddaszadeh Kermani, Moray W. Kidd “The use of Fuzzy Logic to reduce uncertainty in risk management: Analysis of Texas City Oil Refinery Plant Explosion” Post Graduate Research Conference Page 27-30 The University of Manchester, School of MACE (March 26, 2015)

POSTERS

- M. Moghaddaszadeh Kermani, Moray W. Kidd “A decision making model for maintenance strategy: A combined approach analytic hierarchy process (AHP) and fuzzy logic” PGR conference School of MACE, The university of Manchester, 9 April 2014, UK

- M. Moghaddaszadeh Kermani, Moray W. Kidd “Strategic Decision Making Model in Maintenance Management: Is it right time to learn from failures?” Postgraduate Summer Research Showcase, 5th Jun 2015, The university of Manchester, UK

PRESENTATIONS

- M. Moghaddaszadeh Kermani “Supporting a Decision Making Framework In Selecting Maintenance Strategy” Research Workshop Manchester Marriott Victoria & Albert Hotel, November 2013

- M. Moghaddaszadeh Kermani “Improving asset management with implementation of artificial intelligence in decision making”, 4th international Multidisciplinary conferences. The University of Leeds 23rd of Nov 2013
References


SAATY, T. L. 1990. How to make a decision: the analytic hierarchy process. 


WEBER, P., MEDINA-OLIVA, G., SIMON, C. & IUNG, B. 2012. Overview on Bayesian networks applications for dependability, risk analysis and


Appendix A

Discussion in COMADEM conference

Q1- What gaps did you identify with the current maintenance strategy? You suggest there are no formal decision-making tools for CBM. This is simply not true. RCM and reliability data analysis is widely used for CBM selection. Why is your technique better?

The author was discussing that the model proposed for CBM implementation adds to what is currently used with RCM. The concept and strategy was introduced in which the information of current RCM techniques can be used to reach a more effective conclusion. However, it was discussed that the developed model criticises the traditional decision-making approach for selecting CBM techniques in one of the oil process plants and introduced an approach to demonstrate the effectiveness of fuzzy logic in such a decision-making process where there is a degree of uncertainty involved due to the subjective judgements of experts in which, even in RCM techniques, such uncertainties still exist.

Q.2- What is your contribution to date? What data / evidence have you based your proposal on? What is the main difference between your work and Labib’s? What will be your contribution to knowledge?

It was discussed that the proposed model by Labib considers the implementation of maintenance strategy from operational level in which MTTR and MTBF have been considered as a basis of the decision. However, the contribution of the model proposed in COMADEM is to look at the maintenance management from more strategic level whilst considering the effect of two criteria, i.e. cost and safety as the basis of the decision.
Interestingly, the feedback on maintenance model for CBM implementation that has been provided with Prof Ashraf Labib confirms the above views. In the first interview he mentions that:

Labib: *What is interesting in you model is that you have both safety and cost; you have different strategy for different combinations, because in decision making grid (DMG) we only look at frequency and downtime. But here you look at the safety as dimension, which is very interesting, and you have some sort of strategy for each type of combination. Here you have safety dimension which is very interesting dimension to your model. So you can have some sort of strategies depending on the safety. For example here what sort of strategy we can apply high and low, high and high which is CBM. That is very interesting Very good.*

In addition, Labib proposed a different maintenance strategy based on MTTR and MTBF, whereas the proposed model identifies the criticality of machinery for CBM consideration based on cost and safety. In fact, these are the criteria that have not been addressed in the DMG proposed by Labib, which is one of the most challenging parts for identifying the most appropriate trade-off to asset managers.

It was discussed that there is a gap in research for strategic decision analysis in maintenance strategy implementation because the models like DMG ignore the effects of safety. In fact, ignoring the effects of safety in industries like oil and gas could potentially destroy the reputation of a company. For example, BP was banned from continuing its operation in the Gulf of Mexico. Also, the possible costs of failure consequences were eliminated as these are difficult to estimate.

*Q.3- How do your findings in this research align with strategic decision analysis?*
The paper discusses the current gaps in decision-making about critical equipment in real practice. Discussion on decision-making for CBM should not only be limited to the operational level as the criticality of CBM implementation for each machine might vary with respect to the concerns of top level managers. In fact, this model indicates that DMG might be appropriate for the manufacturing industry but the implementation of such a model is not acceptable in the oil and gas industry. This is because there are essential strategic dimensions that have not been considered in DMG. The findings of the paper can be considered as follows:

- Introduce a culture for asset management that highlights the need to look at the CBM implementation not only from an operational level but also a strategic level.
- Demonstrate how fuzzy logic can be applied to CBM. The research demonstrates the effectiveness of fuzzy logic for CBM implementation from a strategic level.
- Propose a decision-making framework. The research demonstrates that the application of AHP combined with fuzzy logic provides a decision-making framework.

Q4-How have you used the case study? Are there any recommendations related to the case study?

Based on primary and secondary data, the paper will explore the main challenges for maintenance strategy selection in the oil and gas sector. Traditional maintenance selection practices are challenged and new methods are proposed. The paper considers a DMG to evaluate the appropriateness of the decision made to implement condition-based techniques. The research output suggests that in many cases the total
life cycle cost could be considerably reduced using the proposed decision-making framework. The current decision-making framework follows a seven step process including:

- Step 1: Establish current production availability performance and review maintenance practice.
- Step 2: Define the target performance and identify feasible alternative maintenance strategy options.
- Step 3: Identify the evaluation criteria.
- Step 4: Identify the stakeholders, i.e. subject matter experts, decision-makers, maintenance managers and production managers.
- Step 5: Apply the MCDM method to generate outputs (the proposed most appropriate maintenance strategy).
- Step 6: Engage stakeholders to evaluate output from Step 5.
- Step 7: Implement the maintenance strategy and re-evaluate at time (t) – return to Step 1.

Note: Time (t) will depend on local operating conditions and local performance goals.

The case study was used to identify the existing gap in decision analysis in real practice i.e. the simple add up procedure was used for selecting critical equipment and hence to decide on CBM. The approach used locally seems to ignore the costs of unforeseen failure and its consequential production losses. The following are some more recommendations:

a) The model suggests that the criticality level of CBM implementation for machinery could change when the decision-making is considered from a more
strategic perspective, and this could potentially reduce unnecessary investment in condition maintenance techniques for certain pieces of equipment within the oil process plant.

b) The fuzzy AHP models effectively deal with the uncertainty related to imprecise judgements of decision-makers and experts by quantifying their qualitative data.

c) The results illustrated that CBM is not the only way to improve the safety of a plant. Investment in fixed time maintenance (FTM) and design out maintenance (DOM) could effectively improve the level of safety in the process plant depending on each machine specification.

Q.5- How will this be applied to a real industrial plant?

Basically, it is necessary to conduct in-depth interviews with top level management. The semi-structured interview would provide the necessary information to consider maintenance strategy implementation from a strategic level. Then, based on the data gathered the two stage model could be restructured according to the requirements of industry and plant specification.

Q.6- Why have only cost and safety been considered?

This question is one the main motivations for developing a multi-dimensional maintenance model. This feedback has been taken on board and critical modifications have been made whilst developing SDMM.

Q.7- Can you elaborate more on the fuzzy logic results? What is the y axis? How did you select your x and y axis?
Basically, there is an X, Y and Z axis. X and Y represent the level of safety and cost and Z represents the criticality level for CBM implementation for each machine in the plant. For each machine, it is necessary to have two numbers, i.e. a number for safety between 0-1 in which 0 represents a situation that is completely safe and 1 which is for when the probability of failure is assumed to be 100%. A number is allocated for cost between 0 and 100 which represents the unit of cost. Once these numbers are obtained for each machine (either from CMMS or expert judgment) then the Z axis illustrates the criticality level of CBM implementation.

In order to calculate the unit cost, the following parameters need to be considered:

- Operational level cost + Cost of condition based maintenance + Cost of machines’ failure consequences to other parts of plant + its consequential production losses
- Operational level i.e. Cost of condition based maintenance [Vibration analysis costs (including labour, interpretation of results and costs of remedial work) + Lube oil analysis costs (including labour, interpretation of results and costs of remedial work) + Cost of equipment failure (all equipment) + Costs involved overhauling critical items on a regular basis (man-hours and materials) + Cost of equipment failures (unforeseen, operator error and equipment subject to breakdown maintenance) + Costs involved with routine lube oil changes]

Q.8- Regarding the AHP results, how did you calculate the scale values for AHP? Where did the data come from?

AHP requires an expert judgement for each machine. Therefore, hypothetical scenarios are defined for Machines A and B. The hypothetical judgement has been
considered to assess different scenarios which demonstrate the application of AHP throughout the model, and to present how the results might change due to different expert judgements. This was the basic reason why AHP was applied in the second stage where the criticality of CBM is known through a fuzzy logic stage and there is a need to prioritise and compare other maintenance strategies like FTM, DOM or RTF.

More importantly, AHP enables decision-makers to compare the sensitivity of maintenance alternatives. This means that the priority of the maintenance strategy might change depending on the requirement of the plant. However, essential improvements have been made while considering AHP during SDMM development to simulate the behaviour of the maintenance department.
Appendix B

Samples of interviews transcripts with Industrial and academic experts

The criticality assessment method used for a BP oil process plant was explained to Mr. Tom Lenahan. It was explained that there are five criteria that have been considered in the plant to evaluate the criticality assessment of components, using the subjective judgement of decision-makers in the plant and the simple adding up process for the criticality ranking.

The proposed model to improve such decision-making was discussed briefly and the following questions were asked to get feedback on the strengths and weaknesses of the model whilst validating the approach and criteria used as inputs to the model.

The first Interview with Mr. Tom Lenahan

Questions: I would like to validate the criteria that has been taken into account to my model from your perspective as you have been working in the oil and gas industry for more than couples of decades . I am arguing that most of the people on the plant who are usually working in maintenance department look at the problem from operational perspective, and I argued that maintenance strategy need to be look at from strategic perspective to improve the performance of maintenance management. This is in fact one of the most challenging point of companies who faced catastrophic, for instance the BP considered cost cut policy for maintenance department, which resulted in Texas City Refinery Explosion. Such attitudes towards maintenance effect overall performance of company and also have very negative effect on company image.

Let me elaborate more on what I mean by strategic decision making for maintenance management, there are the decision that enables managers to identify the critical
components, equipments or process within the plant which could potentially improve the availability, reliability and safety of the plant and result a good return on investment, have you ever get involved in any scenario like this during your last few years? Are there any traditional or new strategies that you have experienced it?

Tom: Well, I am not sure whether it is relevant to you discussion, the techniques that we used to apply is RCM, because there are sort of questions that RCM asks, first of all how critical is these piece of equipment, then are the reasons that it can fail and then what are the maintenance options used in order to prevent that failure, and during my 30 years of experience, I guest RCM is the only techniques that I have been involved, but I know that in most companies there are kind of decision making matrixes that are used and again it depends on the culture of company what to consider in these matrixes. One of thing that I picked up during RCM practice, something was perusing senior management attitudes towards maintenance; I think it is based on where the decision management here in maintenance costs on an investment. One of the things that you mentioned is to look at the problem from strategic angel, then it must be an investment for it and it cost. I mean cost is the money that we need to spend in some way, but investment is the money that we invest in order to earn more money, and one of the questions that you asked was, it is possible to make an investment in maintenance? My answer would be yes, because if you invest in reliability of plant it means that you are investing in the life of the asset, but unfortunately I think in most companies still the main concern is cost, which is led to the cost cutting culture. There one thing puzzles me, I wonder if the senior management of companies really understand what maintenance is, you know, what are the parameters, and what it actually can do, what would be the consequences if you do not carry out maintenance properly.
If you got cut costing exercise around the plant, and still cut cost some of the maintenance budge, it surly, you might not be able to do maintenance properly and it means that you waste maintenance, and if you waste maintenance, specially preventive maintenance, it will off course effects on maintenance planning because, diagram that uses as map, call the machine that requires maintenance, and the diagram shows the interaction between corrective maintenance and preventive maintenance. In other word if you don’t do the enough preventive maintenance then corrective maintenance goes up, but the other consequences of that is spend more and more and more money on corrective maintenance and do less and less and less in preventive maintenance so the percentages on money investment in each strategy goes up and down.

And so you even do less preventive maintenance, and if you do less preventive maintenance you need to do more corrective maintenance and it is like a cycle, and off course the ultimate consequence of that would be kind of catastrophic in the plant, and there are many catastrophic around the world because of these attitudes.

Me: Just to conclude what you said that: As far as I understand, you believe that most of the companies look at the maintenance as cost and they need look at maintenance from more strategic perspective. (Tom: Yes, that right),

Questions: Do you know any company that looks at the maintenance as a strategic perspective?

Tom: Not really, I think there is big misunderstanding what maintenance is really, in some cases if you cost cut to save, the benefit for immediate, for example if you reduce $10 million to $8 million, so you saved $2million, so the people in who are responsible for maintenance tell the senior management that there would be
consequences which could be medium or long term, so if you cut the maintenance budget with $2 million, the plant might shutdown in two years, which is a problem, the people cut the maintenance budget do not care about what you are talking about, it is fortune because the benefit is immediate but the consequences is the longer term, but the consequence when they happened, they have many, many, many times over impact and I worked with company during the commissioning, leave thing behind they decided to rushed the commissioning, and it was all about cost because there was penalties for start date of commissioning of the plant, but unfortunately, by doing that they over heated some of the component within the plant and few days later the plant has to shutdown and it cost $25 million, so as I said these are effect of concerning about cost, by the other side of it is, seems that many senior manager do not come from technical background, and lots of them cannot understand what the people in shop floor saying,(Me: because they are speaking in different languages), and they do not understand that is maintenance, one good solution is to provide some training courses about maintenance, so they can at least have an idea what maintenance people are talking about. Lots of senior managers come from different background, on the other side, people on the production, they know and are aware of maintenance but there are lots of pressures on them for production and that is why you have always conflict between production and maintenance but one of the thing that you just mentions couple of minutes ago was quit right and it is the extension of what I have just talked about, is the idea that they are speaking in different language. The senior always talk about money, and they only think of results and not care about the mechanism that achieve those results, another expert team and group need to take care of keep the plant reliable, etc. Well, that cost too much for some management groups, so the people in maintenance level, they do not have a good
Me: I was trying to elaborate that the key survival for looking to maintenance from strategic perspective, is to find out what are the critical equipments and put the investment on the heart of the problem as maintenance management has got the budget but they are not sure where to spend the budget. Techniques like RCM is good and widespread approach but many companies ignore to use these techniques by saying that it is very complicated or costly. (Tom: yes, you are right) like the Paul Wheelhouse who is the chairman of the company that is running RCM, and told me RCM found for many company as not being user-friendly and hard to follow. Where his company has an experience of training an asset staff for couple of weeks it cost the company more than £100000 but they refused to continue and implement RCM in their asset as they claimed that it is very complicated procedures.

So I was trying to propose an intelligent system, which needs to have certain inputs and provide the decision maker the most critical parts of an asset. Each input would be consider the view of one manager in the field and then try to combine their view without requiring the technical understanding of procedures. In other word, the proposed model extending RCM techniques in way that become much easier to be understand within the organisation. And I was trying identifying the process, in which the decision is make for such criticality assessment methods.

**Question:** According to your experience, such a decision making process is it a well-defined process? is it in flowchart somewhere, or is it rational decisions?
Tom: I am sure that there are example of these and some companies had got formal procedures that deal with these decision making process, but I would start of the idea, as you said, strategic decision making, it is important to define what is critical equipment and what do we mean by critical? So there is formal definition within industry, which defines criticality i.e. if the piece of equipment fails what effect could it have, and the first part of criticality is safety, what hazards would it present? Would it kill 100 peoples, and then the next stage step from that is that would it interrupt production that is were the business point of view comes into interest, if so how much does it cost to put the plant in its working state and how long does it take? There is criticality, umm, but the next step one, is when you need a practice and judgment thing.

**Question:** According to your experience, what managers or who do you think get involved in such a decision making process? As you maintained the steering group, etc.?

Tom: there is another problem from business point of view, any exercises like criticality is very time consuming, what a common practices a lot of companies do is the senior management engaged the strategy then implement it, I think need the mixture, if you need to chance the programme, you need the champion,

So you need to identify what is the criticality at first, and second what are the critical equipments and third, you need the technical people, i.e. plant manager, maintenance managers, supervisors, etc. But, still need the champion by senior management, otherwise you lost.

**Question:** what other criteria you might be think of? Any like, production, operation rate, reliability, etc. And also if different middle manager likes safety production,
maintenance, etc, go to the plant and provide list of critical component? How would you recommend to rate each criterion (managers view i.e. safety operation, etc.) Do you think give numerical numbers for each criterion is appropriate? Do we need to improve simple numerical approach by more intelligent techniques?

Tom: really the first two are the big once, Safety and production interruption that is cost and the loss of production.

“Tom answering what method you use for combining the criteria”

If I was plant manager, of course this the way I am doing it, thing that I do get together people and manager on the plant and make a brain storm section to say what do we mean by criticality and that would generate the criteria, what does that mean, is it only about safety and production or other thing that we need to think about, like length of time to repair, but I think to get to that stage you have to gusset the people imagination, I think the best way to doing it is the good brain storm to actually generate that criteria because you need to know that absolutely, what are the criteria that we need to find the criticality, and after that I will bring an consultant to the practical companies, Companies like ABB, their consultant are all functional experts, which means 25-30 years of experience of people who actually do the job in the plant, and what I do, I will carry on a parallel study, I get the list of criteria, let go to the plant, distribute the task, you look at this, you look at that and each do it separately, and then we come up with the list, then independent of that I would choice one person to say, can you tell us what are the criticality and go to the plant and tell us what you think.

But one of thing that I found it in industry is that people like to jump to the solution very quickly, you have got to spend some times in problem, you have got to define
what it is, the idea is that in any situation like this what we called hard problem, the
problems that cannot only be fixed by calculation and matrixes and that sort of thing
just need the have the right equipment, etc, you know, and you also have got soft
problems which is about the people, judgment, experience, human reliability and all
that sort of thing, and these things are much harder to get into and what you got to
do, you got a exposed, if you do the that brain storming exercise, I guest one of the
output is the education of the situation.

You are not only looking for the criteria in themselves, but also you need to look at
why the people are using those criteria to judgment whether the things in plant are
critical. I use it because I think, and then you might make an assumption on equal
value system or whatever for each system and you can start to build that up.

In lots of case what happens this is kind of an agreement between people on the
plant. And then you go with that as starting point , I think there is another important
thing, whatever you proposed is very good starting point and then use it in the plant
and see how it works, and then you test it and see what result you can get and then
you need to so if it need any improvement depending on the plant.

Because is almost impossible to create one model and get the best result in the first
step, it might require some chances or whatever, and for instance when you
implement the model you need to say we try that and did not get want we want yet
then modified it and chance it is this way or, etc. So if I was maintenance manager
this is what I would do.

Me: very good point that you mentioned Even though you have calculated and
consider the criteria you have the concern about human, if you calculate the
criticality only based on machine it is not enough because the people who are running the plant are also in the great importance.

**Question:** I would like to ask about any uncertainty that you might think in the next couple of decades that need to be considering in decision making of critical component and hence maintenance strategy from strategic perspective? Do you have any experience facing such changes?

*Tom:* Well, I think once of the concern that I have got as maintenance practitioner is that majority of maintenance issues and problems are actually generated much earlier during design and project building stage, and I know why that is, because their concern about their project so they may selection of what they do, I used to work as maintenance and is about how to design a plant and most of the design stages is about selection and connection, you buy piece of equipment and connecting them together, you got pump and connect it to ..., and so on, and then it is all about what you select, and a lots of maintenance issues today is just because the selection made during design or project construction stage was in the wrong ways, and there are lots of thing that you look at them at shallow level and then when you start to look at them in deeper level why is it like this, if you look at plant drawing of any process within the plant, for instance if you look at piping of pump, and look at the things that causes problems like the piping connecting pumps to compressors one of the main problem is called cavitation when you get vacuum bottles and that sustain the chance of pressure, usually that is rotter bald, one of the thing that cause cavitation is right angel bends,

*My main criteria would be asking the main question, how we can eliminate maintenance, what is we have to do to make it easier for self maintenance. So*
elimination is important for maintenance, it could be technology improvement help these kind of things.

The Second Interview with Mr. Tom Lenahan

Once the SDMM was developed, it was presented to the experts to get feedback. The SDMM was explained to Tom whilst discussing the inputs considered in the model for the BP case study, i.e. BP Texas City disaster. It is important to note that the comments provided by Tom have been considered to improve the rule evaluation phase of fuzzy logic. The following are the highlights of the discussion during the interview.

Tom: My question to your model is, you have a Multi-level approach, sort of multi element, you used fuzzy logic and end up to certain coordinates and then calculate the criticality and use the judgment to get an overall criticality, Would it be actually the same if you set those like 5 figures and average them out? Where would you actually end up? Would it be the same as what you got there? I am just wondering if you just get the same results as the numerical assessment.

Me: Basically, this is the reason why I decided to applied fuzzy logic, because legally it is not acceptable to make comparison between safety and cost where you ended up with finding a trade-off between cost and safety. By fuzzy logic the specific rules have been allocated to eliminate such concern.

Tom: It better to ask my question in other way round, if you used oil fashioned criticality assessment method, would you get the same answer to your model?

Me: Very good questions, basically when we start doing research on how it is possible to improve old fashion criticality assessment method on BP process plant.
And this model is improving simple add up numerical approach by replacing Fuzzy logic which gives you a region of gray area instead of black and white.

*Tom:* *My basic questions are that, do you get different answers?*

Me: Yes off course, we are trying to get the real data to train the model, but we could not get them but we show how it differs based on hypothetical examples, which the result would be different, my question to you would be do you know still in industrial plant they are using such simple add up approaches.

*Tom:* *It depends on what you mean by criticality, the experience I have got with criticality is about fire fighting for maintenance. That criticality is looking for reducing the consequence of failure; here is the list of equipment, if any of these fails what would be the big impacts and what consequences it will produce, and those that have got the medium chance of failure will be allocated as highly critical and goes to the top of the list.*

*I think what you are talking about is more strategic and interestingly you have got different elements, you talk about cost, operation, etc. One the things, to me and my experience safety is the one that stand in its own and everything else is on the other side, The safety one has got the biggest impact you know, I am wandering, I am not clear what is the exact output of fuzz logic is, are you trying to some sort of consensus and what answers?*

Me: One of the reasons that I highlighted safety in the model is that when quantitative risk assessment (QRA) carry out in industry like oil and gas, etc. They usually end up with too many item to be critical as there are many machines that have got the medium to low likelihoood of failure but if its fails it with make a
catastrophic incident in plant. So conducting QRA and ending up with too many time to be critical which requires huge amount of investment so the result of QRA need to be short listed in some other ways in which SDDM could effectively improve such a decision making more intelligently.

*Tom:* But there is thing that I am struggling, today there is one thing that is safety that need to be in the first priorities. I am wondering if you can deal with this concern, I do not feel you can optimize something with safety and cost?

Me: thank you very much for very good comment, as I get the same comment from my supervisor who is always emphasizing that we cannot compare safety with cost and so on, therefore I modified the model by changing the rules in the fuzzy logic where if the Safety was in high criticality then the output membership function would be considered to be highly critical regardless of the criticality of other criteria.

Basically, when you would like to use fuzzy logic in such research you need to define curtain inputs, for instance we have got the concern of safety, reliability, operation, cost then you would apply rules within each, and have output to indicate the criticality of each of these dimensions. And when you are about to assign the rules in strategic fuzzy logic when we combine the view of safety, to reliability, to operation and cost, we defined the overall criticality of component to be high if the safety of the item considered to be very high irrespective of others, and so on

*Tom:* yes, I understand, so if you take another case if the safety is low but the reliability was high and cost is high would that then considered to be high critical?

Me: Well, it depends what you want to define for the model, this could be the asset manager or expert judgment, but for the initial stage we develop and approach as a
starting point, it is the way how to quantify the qualitative data. Like that numerical judgments will be transfer to the fuzzy logic to be use as based of precise decisions. The advance phase of model would be when you work on how the system generates rules in itself in which it could be a PhD in its own.

Tom: Yes safety is in its own, so in the case of having safety low you would have chance to go for optimization of other factor. Or safety is medium other factor might become important as well, or in the case of low safety.

Let me generalize it, safety has got a quantity, if the other component has got a lower quantity then safety is a determine, then if the safety is medium and the other three criteria be high then the output would be high. But if other three were low we might not be able to say the overall criticality is low because still the minimum requirement of safety needs to be met. Safety people do not care about the cost,

Me: Very good point that you raise, this is where we need to re arrange the Fuzzy logic rule allocation phase, considering safety in the first priority.

Tom: I think if you work on the rule evaluation phase it will change your map, and one of the good practice is to keep the safety in high and see how other parameter can influence your map. Safety is the limit, and the general rules would be depending on the value of safety that would be the minimum value of output determine, if the safety is high the output is high if the safety is medium then the output could be minimum and/or it is low, it could be any result in output and the role of other criteria can be highlight.

And the other question I would have, if it came out of that, in what point of view are assessing the criticality, because you may have case safety is high and is cost, so it is
effecting reliability and so it effecting production, Obviously the decision you are trying to come is to trying to end up with some sort of action being critical, because Safety is highly critical, and by modifying rules it possible to achieve what is needed, for instance assigning safety as being low determine the minimum value of the output with respect to value of others, and if the safety is going to be high the minimum output need to be high.

Tom continued: when you look at the criticality safety is on its own, anything else depending on safety and so if you look at on the most criticality hierarchy, the top level is safety, and then we don’t want the equipment to fails but if it fails would it have any consequences, the next level normally is operation, what effect does it have on production. Will it stop or interrupt or reduce production, etc. Umm the next level down is how all these thing affect each other, any direct or indirect cost.

So in the criticality hierarchy is top level is safety, then production and then cost and lastly technical.

Me: One of the ways that I tried to validate the model was trying to pick up the failure case in oil and gas industry, and trying to find the attitudes of management towards maintenance management, whether it is culture of cost cutting for safety in the first priority. I compare the behaviour of managers before and after failures, and giving the relative importance of one criterion with respect to other.

Tom: it is might be interest to look at it in more detail. It is worth mentioning that he culture continues replacement within a plant may not be appropriate, may you got to replace a pump and manufacturer provide specific information about that pump and suggestion about the replacement time, etc, then you can schedule for that particular date to replace the equipment, however it is not necessary.
Discussion with the academic professional

The first interview with Prof Ashraf Labib

Me: Basically, what I meant by strategic maintenance management is the work of Northern and Kaplan. Considering different criteria i.e. reliability, availability, safety, asset integrity, cost, etc.

Labib: When you say upstream or downstream, why did you differentiate a difference between upstream and downstream project with respect to as being strategic?

Me: according to the case study analysis when the oil production process started after while due to the availability of oil well capacity the management department decided to use all the redundant components in the main process of production, in other words the redundancy of all component has been eliminated and the plant faced to many break down records,

Labib: so they had two lines, but they had more wonder ability in case anything goes wrong?

Me: yes, when I had a chance to attend your lecture on DMG, I pick up an idea that wow I can modify DMG from more strategic perspective to reflect the concern of oil and gas industry.

Labib: Yes, you can add different dimension do the DMG,

Me: So I started to develop your model based on the needs for upstream and downstream plants. Why do we need to consider oil and gas as being strategic? There are four dimension in strategic management introduce by Norton and Kaplan which can be named in maintenance management as technical, operational, managerial and commercial dimensions. In fact SDMM helps you to find the heart of
problem with respect to these perspectives and help you to invest in the right place. In my research I highlighted that maintenance objectives are not meeting organizational objectives.

Labib: yes that is really true, there is need to align maintenance department objective with organizational objectives.

Me: Financial perspective deal with maintenance cost and production cost loss, it will investigate for instance if there was failure for the component what would be its consequences in term of losing production and cost of maintenance.

Other perspective is safety which is concern of high level managers, especially in recent years when there have been many catastrophic failures in oil and gas industry. The Quantitative Risk Assessment (QRA) techniques used to apply to address the concern of safety however it suffers from some limitation for instance it ends up to proposed with many item to be critical.

Moreover, from operational perspective where production and maintenance manager would like to minimize downtime and number of failure frequency, your approach has been considered in SDMM. And finally for technical perspective, the reliability of component in term of its pattern of failure and it’s important to reliability block diagram of the whole asset will be considered as input to SDMM. In other word how important is a component for the operation of whole asset.

Basically, likelihood and consequence of failure considered for safety concern, moreover downtime and failure frequency considered for operational concern, the maintenance cost and production cost lost for financial perspective. And also
machine importance with respect to reliability block diagram and pattern of failure for learning and growth perspective.

Ashraf asked: on this model, here when you saying learning and growth, why do you have RBD and Pattern of Failure?

Me: When you analysis the importance of component with the whole asset and its pattern of failure, and asked the manger to invest on a specific component for specific maintenance strategy like CBM, there is possibility that the asset manager accept or reject the request of maintenance department, therefore learning and growth perspective need to monitor and review the performance of each component within the asset every quarterly and report back to the decision makers and aware them about their consequence of decisions.

Whenever all 4 fuzzy logic with 2 inputs provide the criticality of each machine to be low, medium or high. Therefore, each fuzzy logic has three-outputs i.e. low, medium and high which will be considered as inputs to the main strategic fuzzy logic. This model in fact tries to improve current approach used in criticality ranking method in real practice by applying artificial intelligent (AI). The rule evaluation phase is the most important part fuzzy logic in which 12 categories has been identified for defining rules.

This is the end of first phase of research where it provides the short list of components, by combing the concern of different middle managers to find the most critical components.

Labib: what is the vertical axis in the Fuzzy logic results? And what is the scale?
Me: it is presenting the criticality level of each component and it is 0-1 and/or 0-100, first bit of model help to improve current criticality assessment method used in the industry, and the second phase focus on make in decision in maintenance strategy. In the upstream asset, according to the interview with the maintenance leader in Shell Company, they used Failure Model Effective Criticality Analysis (FMECA) and based on these analysis they make the decision on the most critical components.

Labib (Min 32:02): What is interesting in you model is that you have both safety and cost, you could different strategy for different combinations. Because in decision making Grid we only look at frequency and downtime, but here you look at the safety as dimension, which is very interesting, and you have some sort of strategy for each type of combination. Here you have safety dimension which is very interesting dimension to your model. So you can have some sort of strategies depending on the safety. For example here what sort of strategy we can apply high and low, high and high which is CBM. That is very interesting Very good.

Me: This is the first paper and then it can goes on the second paper which we try applied AHP using case studies and try to validated the model, first case study was the one I explained about BP oil production platform where they management decided to used all installed redundant parts in the main production which the production rate increase to more than 150% but the asset face to many breakdown for small, medium and high rotating equipments and therefore management decided to identify the most critical components for CBM implementation. There are four criteria considered in the criticality assessment method i.e. operating point, cost, safety and operational reliability.
In our model, AHP used only for the component that have been selected as being the most critical part, So AHP goal is to select the most appropriate maintenance strategy for the most critical component, there are 4 criteria and there are three alternative maintenance strategy i.e. Fix time maintenance, condition based monitoring and design out maintenance. There could be and skill level upgraded strategy be updated into model. However, for the critical part of the plant run to failure (RTF) strategy is not acceptable at all because nobody wants to have failure for the most critical component of the asset.

This is where we get engaged the senior manager on decision making process, and let them know what would be there consequences of their decision making.

*Labib asked: How do you have the importance of the top ones?*

Me: imagine we have machine A, which is the outcome of the first phase of research, and here we need to have the view of senior managers to give use their own concern on asset management. For instance, long time ago in oil and gas industry, the only concern was only cost, however due to recent catastrophic incident the safety cannot be ignored any more. So the relative impotence of one criterion with respect to other criteria will be given with the person who is in charge of asset management. Here it is where we present how the consequence of decision can be track in the asset performance. Basically, the model is providing an opportunity for maintenance department to track the actions of asset manager in the performance of asset.

In terms of industrial implementation, this model is just make the recommendation to the asset manager the best alternative maintenance strategy, however due to many reason asset manager might not want to invest on the strategy that the model propose but it advantage of model is that it provides an opportunity to show what are the
tangible consequences for such a decision making culture or behaviour that can be used for lesson learned which can leads to changes on the culture of decision making.

Ashraf Labib: It is very good model, you are using hybrid methods i.e. AHP and Fuzzy logic which is very good, you know on the paper that I wrote that I used Fuzzy and AHP for selecting Maintenance strategy. But my model was much much less in terms of scale which not included risk, safety which you included.( Minutes 40:02 )and also I like here that you would like to applied the model in some applications in industry. It would be nice to show to industry, and investigate how this can be demonstrated in industry. How this process can be shown to the industry.

Me: in order to discuss how the model can be implemented it is important to note that most of the oil and gas plants have their own databases which might recorded historic failure data, QRA, etc. The SDMM will use the both quantitative and qualitative data for A-Z components, to identify top critical components for instance A-B-C-D. Accordingly the subjective judgment of the asset manager will indicate the best maintenance strategy.

To make the importance of the models more clearer I would like to explain the BP conflict when Tony Hayward became a chief executive of company in 2007 and emphasised that we put the safety in the first priority however the BP was experiencing catastrophic indecent like Deepwater horizon oil spill, Texas city and other explosion. Such experiences in fact confirmed that the safety was not in first priority in the real practice of the cultural or organisation.

With the aid of SDMM the maintenance department provides the list of most importance parts for implementing maintenance strategies and therefore depending
on the concern of asset manager appropriate maintenance strategy can be implemented. SDMM provides an opportunity to track the consequence of decision made with asset manager towards maintenance management. In which it give the feedbacks to asset managers every quarterly to increase their awareness about the consequences of their decisions. And that feedbacks provide a learning and growth for the asset and it is way towards continues improvement.

Ashraf: you have learning and growth here in model, are we allocating any resources as budget on of these strategy?

Me: Basically, there is an application on Reliasoft that provide a chance to look at the budget and financial analysis. But I did not go through it and it could be a future work of research.

Ashraf: about Fuzzy logic, I am trying to understand the functions of every part of the model. The fuzzy logic according to your model will give me some sort of criticality that you provide the most critical short list and applied AHP, In fact AHP give you the best alternative to select for maintenance strategy. AHP can give you two things either a Choose or allocation of resources when you have the budget and would like to distribute the budget depending on the percentage of criticality for each component. In your case I believe you select the highest of to go to the AHP model where AHP used for a selection not resource allocation.

Me: Probability that resource allocation can be another part that we can add it to the model.

Labib: yes as expansion, but I don’t want to change your model. Your model is very interesting (Min 45:10). It looks very interesting.
Me: you feedback on my model is really valuable. Another point that I would like to add, please look at RBD, I was thinking to look at that RBD can try to combine it with the lesson learn from failures. For instance imagine an asset and it process flow sheets and assume we know how the production line will be produce a product and we provided a RBD of whole asset, while in the other hand we have RBD that constructed from Fault three analysis when we have the failure and analysis the event by producing FTA and creating RBD which is process of learning. And I was thinking how that learn from failure approach can be used in the model? Instead of RBD of whole asset why not using RBD of event from FTA? What do you think?

Labib: Is it possible to show me the fuzzy logic rule evaluation phase? I am trying to understand why you used Fuzzy logic but not AHP to priorities criticality. Why Fuzzy Logic used? As challenge why you did used Fuzzy Logic not AHP?

Me: Very good question, I am getting ready to viva examination now, basically when we discuss strategic perspective we need to consider many criteria. We already evaluate the fuzziness for each set of inputs within itself for instance in terms of operational perspective, down time and failure frequency had an opportunity to be evaluate in the concept of fuzziness whereas to deal with the concept of strategic management, the concept of fuzziness need to be applied between different dimensions i.e. operation, technical, managerial and financial. In fact the fuzziness of one dimension to the others can be examined through applying fuzzy logic. Basically the concept of gray area between 0-1 is tested from operational perspective with DMG, however this concept need to be developed by testing one dimensions with respect to other.
Labib: Okay I understand, can you show me the membership function of one of them? Is it trapezoidal or is it triangular, etc?

Me: I used a trapezoidal, can you explained what might be wrong with other types.

Labib: right, what you did is correct, because some people use triangular, but it need to have shoulder as you did. Why, because suppose the following picture is low, medium and high, So when you have this line here (in the low M.F), the has the value of (u) which is 0-1 and also the same line give the same value of (u) for M.F high let say 0.8, the one afterward which should be even higher, the (u) of it would be point 0.6 or 0.5, because the slop is going down which does not make sense because you are increasing this way which should be higher, this is reason why the M.F should be like a shoulder not triangular. This is what you did in this model, because this means that the more you go high it is the same level which is the same (u). And the same logic applied at end of membership function. You know some times people write book and show the low, medium and high membership functions like triangular which is wrong.

Me: what a about some curve shape membership functions? What is the difference between these types, I cannot understand?

Labib: you can use curve, this is just minimized the among of calculation, if you use Matlab do the calculation for you, but if do the calculation by hand, it would become very difficult if you chose the curve shape. It is simplistic way when you use the trapezoidal shapes as what you did here in the model, and to the fuzziness it is important to highlight what is the shape of membership functions. This why you are using Fuzzy logic Not AHP, because in AHP you can have the same columns of you input to model and each of these columns could be an criteria, here you assuming
the scoring high on RBD, or high in MTBF, or high in Safety, or high in Cost will give you Very Highly Critical (VHC). But there is implicit assumption, here you making is that each of these criteria is equality weighted. It means that you consider Cost is equal to Safety, is equal to MTTR and is equal MTBF

Me: yes I assumed they are equality weighted but in order to overcome this concern the rule evaluation phase have been modified in way that safety has got the most priority with respect to others and so on. This where I need to have you idea, initial stage of calculation I considered them all to be equal as an assuming, what do you think?

Labib: it depends on the managers and the problem is this good assumption or it is reasonable assumption or is it strict assumption.

Me: Basically, what you are saying is depends on manager and culture of organisation, I then need to modify the model because know a days specially in oil and gas industry the concern of safety cannot be equal to any other criteria and is not logically acceptable to compare the cost and safety for investment on asset.

Labib: You are Appling the rules to select the rules, for example, can I see the categories of your rules allocation. This is very important part of research; here you applying the way clustering the rules, this is the most important part. Your future work could be How do you generate rules from data in itself? Using works like “At least, at most, etc” In fact, in operational research the will be called “rough set method”. Do you have data about this model?? What sort of data do you have?

Me: I am currently looked at how to generate rules using some programming because for the category A and B and even C it is possible to use you common sense
to find out the number of rules that exist, however it become very complicated when it goes down to F and G.

Labib: Your model looks perfect, but still I have a bit concern about assuming they are all equally weighted because if I am decision maker specially in safety, and look at your model and see that you consider safety equal cost or something else it would not be acceptable. Safety for some people is very very important, so maybe you could have difference manager that have different views and how to combine their views. This could be another paper i.e. “Combining the importance of the criteria from different stakeholders”

So how do you decide which manager is more important? Which one of the manager has got the most important view? You can say in PhD that this is an assumption, and this assumption can be work in future work.

Me: yes you are right, but this concern has been address during fuzzy rule evaluation. In fact my model is criticizing the weight approach to criteria such as safety and cost, in fact the model deal with these concern while defining rules for strategic fuzzy logic and depending on what is needed for each plant the importance of one manager can be define to be more than others such as safety. I argued that it is not simply truth to just assign weights for criteria such as safety and finalise decision based on the ranking obtained. If someone say weighing of safety should be 5 time than cost, one could argue why not 4 times than cost and these subjective judgement will produce different results. However by allocating relative rules in fuzzy logic if the concern of safety was very high the result would be very high irrespective of other criteria and so on. However it is important to note the weighting for different perspective has been considered in AHP where the behaviour of asset manager can
be identified while giving the weights for different perspectives that address the concern of cost, safety and many other factors.

Labib: What I like about this model, is that you close the circle and it is like a feedback loop, and this is nice to have something that is complete, but make sure you have something that external examiner say yet this compared into industry, it is not just an idea. There are two bad extreme in PhD, one extreme is that bringing lots of model to gather and make another model, and complicated thing without adding showing external what is the value of this, so solve this sort of dilemma, you need show the external this model will work, like when you told me I will compared the criticality that my model suggest with what they did considered as the critical part of plant. This is a very good PhD. Remember, when you told me; I am comparing what is currently implementing in industry for CBM selection and what my model has done to improve this selection. This is very good, you must make this amplified it, because you are looking what they are doing, and you are observing what they are doing as research method and then you are developing a model that enhance current approach. Demonstrate that and show what they have and type of machines and what they did and show what you have done and how would you know or/and how would they know that yours is better than them. You have to find arguments that convince the readers that your approach will lead to better results than their existing ones. It is usually very difficult in during period of PhD to verify it, it might take long term.

Me: Specially when it is strategic,

Labib: yes you are right because the strategic is long term in its nature. There are many ways around this to validate the model with other strategies rather than
industrial implementation, So either you can do this, one way for example is prepare a questioner and tell them this is what the model said and this is what you said, which one do you thing is better and can you tell me why? And need to convince them your model is better and just give them the results and say seat with managers who are familiars with these machines and tell them this what you model doing and this what they are doing. So may be because they have the experience your model gives the similar results, which in that case again your model is verified with what they have done. So do it whatever you do it, OR you can have in depth interview through workshop that you may arrange with them, or sending questioners and ask few people to rank things and so and so on that you can compare things.

Ashraf comment and criticism : Your model have got nice combination; you look at the maintenance from strategic perspective, used the concepts of Balance Score Card and try to use fuzzy logic to priorities and AHP to select on maintenance strategy.

May be small criticism to my model could be that your inputs are widely defined, what do I mean by widely defined is that when you are comparing physicist to chemistry or ... it is like a different disciplines compare which each other. You say risk, people wright PhD in risk. When you say safety, safety is very big topic. You are comparing physics to chemistry to biology. Do you know what I mean it is so strategic?

Me: you might be correct, but as far as I know this is the nature of being strategic, you have to consider the view of all these middle managers in order validate that you are looking to the problem from strategic perspective. And SDMM is like a new born baby that needs to be improving gradually.
There is also other concern that I might be facing some difficulties when implementing this model to the industry. The people who are working in industry might argue that they are using techniques like, RCM, FMEA, in the asset and we know where are the most problematic part of the asset, why do we need to use your model? But my answer would be that the results of such techniques will be considered as input to SDMM. Basically, those results of FMECA, RCM, etc. can be considered as inputs to the model. Basically, we can use that lesson learn from techniques to analysis the criticality from strategic perspective like what has been done to BP Texas City disaster.

**The second interview with Prof Ashraf Labib**

Me: There are dimensions that have been taken in to account and I would like to discuss about the inputs to the strategic fuzzy logic. Another point that I would like to discussed with you is the point that you mentioned in the last interview, why did not I used AHP instead of fuzzy logic. One of the concerns that I had with AHP was that each components requires lots of pairwise comparison for each component i.e. increasing number subjective judgments which improve the degree of uncertainties. And this is one of the reasons I was thinking to reduce the number of judgment and uncertainties while applying fuzzy logic and then apply AHP in the second part of the model.

*Ashraf Labib: your answer is adequate but for me to appreciate the use of fuzzy logic, do you expect every decision maker to contribute to fuzzy logic, in which way, for example in the rules or? How would be their contribution?*

Me: Basically, we have got a list of component and applied fuzzy logic to assess criticality of components from A-Z, Some of the inputs are quantitative for instance
MTTR and MTBF, and also from risk perspective there are methods like QRA, FTA, RBD, etc which are quantitative analysis that can be consider as input to the model. But there are some curtain inputs that might require qualitative judgement of decision maker like importance of machine with respect to RBD of asset.

Labib: Although you consider RBD as one of the inputs to your model, there is model called Erik hall Nagel from Denmark end up with the model called FRAM, which is good model for safety, and also Nancey levecon in MIT, she used system dynamic (like water hydraulic, etc) she tried to model safety issues but not using FTA, RBD, but as if it was a system and trying to look at the impact of one factor to other factor, There are some methods around these.

Me: but my contribution of knowledge is not focusing on safety in itself or risk and so on, however my main contribution to knowledge is how these different factor can be combined with each other.

Labib: what do you mean, is it one off excises or different company have different types of inputs.

Me: basically, this is what I am proposing if any industrial plant has strategic concern they can use this model as a base and can be improve depending on their needs and objectives, for instance here the importance of machine with respect to RBD which can be linguistic or in other word qualitative, here is the way we combine the quantitative data with qualitative ones.

Labib: But even just the linguistics ones, how are they making the judgment, can you take me though the process from getting here to here?
Me: For example if that component fails, how that failure effects from financial perspective.

Labib: but here we are looking at this type of failure for example say if the gas turbine it will score high with respect to RBD, for example for other machine like pump it will score low of with respect to RBD, is this the way you considered the view of decision maker in to model?

Me: yes that is right.

Labib: yes I can understand it know, let take another one, for example downtime or failure frequency, do you consider the same concept for the same machine or use the same people to rank this.

Me: No, it would be the same machine; basically the same machine would be evaluated from different perspective.

Labib: very good, very good, I can understand that, so you are going to be selective of top 10 machines or worst machines, and then you are prioritizing them using some sort of engines like fuzzy logic or AHP, based on their impacts on each broad criteria. Is this what you are doing?

Me: Yes, that is right.

Labib: It would be very nice if you show this model works in some organisation that people can understand how it works, it is important to show how someone else can take the model and make it works for their organisation, basically demonstrate that through your methods or survey that look this is method, or even make hypothetical cases, imagine there is gas turbine, compressor and generator for example and this is impact of them in particular criteria, you assume just to show how it works, that in
fuzzy logic this is a membership functions and this is the rules and this is how I am using these values and put them in the system and using afterward AHP and this is the results, and then you can verify it by some people.

Labib Recommendation: Even you can generate data to go through model to show how it will works in overall, this is very important for any PhD, even if it is hypothetical, for instance for DMG imagine list of machine, imagine downtime and failure frequency for each of these machine and if you consider for you model you have 6 dimensions. So it is very important to show how does it work, how these rules are combined from that results so that it works here, so if it works here there is big assumption this could work elsewhere and so one, because decision makers will not give you the model, you are generating model yourself all they give you is data or their judgment and they are not developed the model for PhD.

Imagine I know about gas turbine but you have to scoring for different things, for example when you are choosing machine in assets, chose on high in one side or risky in other side it which might be low, that you making good comparison, because they are not all at the same direction. For instance high in Cost and Low in Risk, ... otherwise you are not be able to compare. Make sure there is variation different type of machines so you can show look in this case we do this and in this case we do that. And so on,

Me: do you think choosing and failure case in the history of oil and gas would be good idea?

Labib: as the secondary data, yes it is very good, in the certain way, yes many people do that, for example in my book, I chose different,
Imagine two machines: one gas turbine (very complicated) and a compressor (not very complicated), and take me through what you would do with these two machines?

Me: basically, imagine a gas turbine, from CMMS we have data about MTTR and MTBF (is the measure of frequency) and then from the concern safety, the machine will be located in other area in the graph and so on.

Labib: Make sure each of these dimensions varies from one to other, because the MTBF is the measure of frequency, someone who knows about what this is, he might argue that this the same scale of the frequency in other matrix, and also for MTTR is the time to repair which is consequence and is down time which is cost, and you make sure that have good answers to it that is the consequence in terms of safety but not cost and the same answer for frequency dimension which is in terms of safety but not number of failure frequency for components, you need to make sure these are all different dimensions.

Me: So I was trying to highlight here from safety perspective I considered likelihood and consequences of safety, and then it goes to the next stage were we get the results with other three inputs, and then we get to the stage where we assigned rules for instance if 3 put of 4 was very high critical then the output MF is highly critical,

Labib: So based on the combination of these scoring you are determining the final results, and these rules will never change?

Me: No, well it depends it can be modify at the beginning before the model runs through whole asset to reflect the concern of asset manager, but once the rules established it need to be remain unchanged for all machineries.
Labib: which is correct, what you are doing is applying different cases to where they are in the surface of decisions, you are plotting, what would be nice to present graphically here is that once have got the results from decision makers each one of these machines will have different place on the surface, draw a circle around the location of each components on the decision results, so they can appreciate what your model dose, otherwise it is difficult with those who are not familiar with this techniques to understand what does this model tell me, you need to plot the machines on each of these graph. In this way you are showing the reader how this works. And then you can verify it, like mechanical, just show by figure how it works, it is not the issue, but you need to show how it works. It is the most important part.

Me: do you think it is required to get engage in real industry for a PhD? Because I concern for my PhD

Labib: So as a PhD all you need to do is to convince a reader, so you can make interview with a person how is not familiar with Fuzzy and AHP, and if they can understand what you are doing, it could be a way of validating. For example John Harris, Tom Lenahan, Paul Wheelhouse, etc, choice people like that and document this interview, and also what they told you to do take it on board.

But verifying in this stage from industry would not help you a lot, but at the end you can do that. For now, you can get engage the expert in the field to show this the model, validate the selected criteria as need to industry.

And also, PhD student make assumptions, and because they forget about their assumptions and they forget to mention them explicitly, they start to believe on their model and forget about their assumptions.
So here you are making a big assumption that need to be mentions, you are assuming here that weights of criteria are equality weighted, because you are saying any 3 out of 4 and so on, some one could argue if it is safety, it is the concern and it is critical so maybe you can verify that, if you can engage the industry for the rules, then you can change the rules on that, and you are designing the model based on the industry concern. And then the expert in industry can generate rules for your model yes that is right, for instance if it is safety it is always high. So you can make an assumption that they are all equally weighted.

Me: So it might be more professional, to go second option, because if I say all is equally weighted then might argue with many researcher, but we can assign specific rules for safety that if any machine has the high criticality in terms of safety it will be consider as begin highly critical.

Labib: yes you can do that and generate rules accordingly and they can get priorities the factors for you,

Me: Probability, I can remain with the rules and consider they are all equality weighted, and I use a case study and in that particular case study I adjust the rules

Labib: Or say from the beginning these whole rules are for oil and gas companies, and you make the sample with them and adjust the rules and you can argue these set of rules is only for this particular set of companies. And may be for another industry nuclear for example it needs to be modified.
Appendix C

Sample of Covering letter for world Class companies

Strategy Developer

Monday, 2 Feb 2014

A Strategic Decision Making Model (SDMM) to improve maintenance strategy selection based on equipment criticality: The case of Oil production Platforms

The increasing demand on productivity improvement requires appropriate maintenance strategy selection based on the equipment criticality. Almost 80% of problems associated with oil production platforms come from 20% of the facilities. Therefore it is crucial to identify the critical parts of the platform while combining operational, technical and strategic perspectives. This is in fact one of the key elements of success for strategic asset management.

The centre of Project Management in the University of Manchester has been working on the development of a Strategic Decision Making Model (SDMM) to identify the critical components in industrial plants. The model used Artificial Intelligent (AI) and Multi-Criteria decision Making (MCDM) tools such as Analytic Hierarchy Process (AHP) which recently adopted due to the dramatic reduction of oil price to improve asset reliability, availability and safety.

We are trying to understand how the developed model (SDMM) can improve the decision making process for maintenance strategy selection towards critical component in the real practice. This research is intended to identify the advantages of SDMM implementation that bring about improved business performance in the long term.

I am writing to ask for your help in this. We have carefully selected a range of companies from upstream sectors to participate in our research and development process. Your collaboration will therefore be very valuable towards ensuring a representative view.

We will share the findings of the research with all participants at no cost. Several word-class companies have already signed on this research project and your participation in this investigation would therefore represent an opportunity for cross learning with leading companies around the world. We very much hope that you will be able to participate. Please feel free to contact us at the below addresses if you have any question.

Sincerely,

Management of Project Research Group

Mohammad.Moghaddaszadehkermani@postragd.manchester.ac.uk
Moray.kidd@manchester.ac.uk
Appendix D

Sample of Email communications with World class companies

From: Joe.Barnes@shell.com

To: Mohammad Moghaddasazdeh Kermani; I.Stanley@shell.com;
Cc: Moray Kidd <Moray.Kidd@manchester.ac.uk>;

Good morning Mohammad,

Rather than organising a visit straight away I think it would be really useful to arrange a call some time to understand fully what you’re doing with the project and how far along you are with the research. As you’ll be aware, oil and gas assets are generally split into SCEs, production critical items and non-critical. They are also separately classified according to the criticality ranking that you’d derive from functional failure mode analysis (and hence maintenance strategy selection). Bad actors analysis therefore generally refers to a functional location’s contribution either to production loss or opex loss. I’d be interested to hear what data inputs you’re using and how you’re applying fuzzy logic to it. Once I understand I can then engage with the right people in the global maintenance community to assess the potential and “fit” into existing systems. I’ve cc’d Ian Stanley from our Projects and Technology group since I think it would be of interest for him to be involved in the call if he’s available.

Best Regards
Joe Barnes

Maintenance Strategy Lead
Brent Charlie Production Improvement Project

Shell U.K. Limited
1 Altens Farm Road, Nigg, Aberdeen, AB12 3FY, United Kingdom

Email: joe.barnes@shell.com