QATAR UNIVERSITY

COLLEGE OF ENGINEERING

SPARE PARTS STRATEGY: A MULTI-CRITERIA SYSTEMATIC CLASSIFICATION APPROACH TO REDUCE INVENTORY COST

BY

KHALED NABEEL AL-KUWARI

A Project Submitted to

the Faculty of the College of

Engineering

in Partial Fulfillment

of the Requirements

for the Degree of

Masters of Science in Engineering Management

June 2018

COMMITTEE PAGE

The members of the Committee approve the Project of Khaled Nabeel ALKuwari defended on 15/04/2018.

Dr. Tarek ElMekkawy
Thesis/Dissertation Supervisor

Dr. Galal Abdella
Committee Member

Dr. Farayi Musharavati
Committee Member

Dr. Murat Kucukvar
Committee Member

Dr. Dinesh Seth
Committee Member

ABSTRACT

AL-KUWARI, KHALED, N., Masters : June : 2018, Masters of Science in Engineering Management

Title: Spare Parts Strategy: A Multi-Criteria Systematic Classification Approach to Reduce Inventory Cost

Supervisor of Project: Tarek El-Mekkawy.

Efficient and effective spare parts management play an essential role for equipment-intensive companies, and many of them struggle with spare parts management issues. Asset and maintenance managers are continuously challenged by decisions involved risk and cost related to a large number of the difference in type and complex in nature spare items. The spare parts nature is formed by a variety of factors such as lead time, operation impact and part cost. One technique of managing these large items is by adopting a systematic classification method to rank the criticality of each item. This classification method is an approach to support management taking the right decision and develop the proper inventory policy. This project is proposing the application of an effective multi-criteria spare parts classification approach. The proposed method is using the analytic hierarchy process (AHP) along with vital, essential and desirable (VED) classification method. The proposed method was tested in a sample of spare part, and the results have shown the applicability of such method in managing spare part.

DEDICATION

I dedicate my project to all my family, my wife and my three kids who have never left my side. A special feeling of gratefulness to my devoted parents, whose words of encouragement for tenacity rings in my ears since my childhood.

ACKNOWLEDGMENTS

I thank all my family members for their constant support and patience during my studies in all my life. My gratitude and appreciation for this work supervision are for Prof. Tarek El-Mekkawy for his continuous guidance and generous assistance. I extend this gratitude to College of Engineering and the OGS upkeep guidance and support.

TABLE OF CONTENTS

DEDICATION iv
ACKNOWLEDGMENTS v
LIST OF TABLES viii
LIST OF FIGURES ix
CHAPTER 1: INTRODUCTION 1
1.1. PROBLEM STATEMENT: 2
1.2. PROJECT GOAL: 3
1.3. RESEARCH METHODOLOGY 3
1.4. REPORT OUTLINE 4
CHAPTER 2: LITERATURE REVIEW 6
2.1 MAINTENANCE PRACTICES AND SPARE PARTS MANAGEMENT 6
2.2 SPARE PARTS CLASSIFICATION METHODS 7
2.3 SUMMARY 10
CHAPTER 3: RESEARCH METHODOLOGY: SPAR PARTS CLASSIFICATIONS 11
3.1 CURRENT PRACTICE: 11
3.2 ISSUES AND GAPS IN THE CURRENT PRACTICES 13
3.3 PROPOSED METHODS 14
3.3.1 CLASSIFICATION OF SPARE PARTS 14
3.3.2 CALCULATING THE AHP SCORE 16
3.3.3 FINDING THE PART CRITICALITY CLASSIFICATION 30
3.4 SUMMARY 34
CHAPTER 4: IMPLANTATION 35
4.1 DATA COLLECTION 35
4.2 PILOT IMPLEMENTATION 36
4.3 RESULT EVALUATION 38
4.4 SUMMARY 39
CHAPTER 5: CONCLUSION AND RECOMMENDATION 40
5.1 PROJECT CONCLUSIONS 40
5.2 RECOMMENDATION AND FUTURE WORK 41
REFERENCES 42

APPENDIX A: FEEDBACKS: 44
APPENDIX B: PRIMARY CRITERIA FEEDBACK ANALYSIS 46

LIST OF TABLES

Table 1: Overview of the main spare parts classification contributes. 8

Table 2: Current Practice Classification 14

Table 3: AHP Scale for Pairwise Comparisons 18

Table 4: Criteria Pairwise Comparison Compute and Normalize 22

Table 5: Primer Criteria Criticality Ranking 22

Table 6: Overall Pairwise Comparison Compute and Normalize..................................26

Table 7: Example for Calculating Part Criticality Score 29

Table 8: Classification Boundaries and Criteria Involvement.......................................33

LIST OF FIGURES

Figure 1: Material Procurement Workflow....................12

Figure 2: Maintenance Classification Matrices....................12

Figure 3: Spare Parts Criteria Analytic Hierarchy....................17

Figure 4: Example of AHP Pairwise Comparison....................19

Figure 5: Example for AHP Primary Criteria Pairwise Comparison....................19

Figure 6: Feedback Sample....................20

Figure 7: Pairwise Analysis Result for the Primary Criteria for One Feedback....................21

Figure 8: Individual SME Ranking for Machine Impact....................23

Figure 9: Individual SME Ranking For Demand Frequency....................24

Figure 10: Individual SME Ranking For Lead Time....................24

Figure 11: Individual SME Ranking For Part Cost....................25

Figure 12: Collective SME Ranking For Machine Impact....................27

Figure 13: Collective SME Ranking For Demand Frequency....................27

Figure 14: Collective SME Ranking For Lead Time....................28

Figure 15: Collective SME Ranking For Part Cost....................28

Figure 16: Spare Parts Criteria Hierarchy....................30

Figure 17: System Boundaries....................32

Figure 18: Classification Boundaries....................33

Figure 19: Spare Parts List....................36

Figure 20: Screen Shot From the Spreadsheet....................37

Figure 21: Ranking Process....................38

CHAPTER 1: INTRODUCTION

System availability is one of the major daily concern for the assets managers in the oil and gas industry. Spare part plays a crucial role in providing support to maintenance practices to avoid system intrabuations. The unavailability of spare parts increases equipment downtime which leads to production and profit loss. For this reason, spare parts management is an essential part of the overall operation management.

The main driver of this research is finding cost-reduction opportunities in the oil and gas industry by enhancing spare parts management policy. Due to a challenging present-day market and price fluctuations, this research is studying current spare parts classification practices and is aimed at introducing a systemic approach to reduce spare parts inventory costs and at the same time improve reliability.

This research proposes a multi-criteria systematic approach toward spare parts management using an analytic hierarchy process (AHP) as a tool for managing inventory in oil and gas sector. The analytic hierarchy process is used in aspects of decision making of the policy of inventory. The unique features of spare parts concerning their needs for managing inventory control and design. This tool will be used in oil and gas sector for the opportunity of saving cost by reducing inventory expenditure and consequently reduce the maintenance cost. This study discusses the use of multi-criteria spare parts classification to improve inventory strategy management and control, in order to provide more support for inventory management decision making.

1.1. PROBLEM STATEMENT:

The oil and gas industry has benefited from the high oil prices in the last decade. Moreover, the focus was more on keeping the production despite any cost. This resulted in less focus on many cost reduction opportunities and less interest in any initiative in this direction. Nowadays, the situation has changed due to the fluctuation in oil and gas sale prices with the increases of uncertainty in the current market. Therefore, the concept of cost optimization become more popular, and different measures have been addressed to look for any cost reduction opportunity. One of the primary cost drivers is the cost associated with spare parts. Many published literature has estimated the cost of carrying maintenance's spare-part as high as 30%-40% of the spare parts value. Based on these facts, the study of the spare parts issue is justifiable.

One of the overlooked issues is the practice of spare part criticality classifications. It has been observed that the classification methods vary significantly within a single division. Some units are using annual consumption value where other are using cost associated with spare parts. Moreover, the term critical might have different meaning depending on the area of focus of different perspective; critical items from a maintenance perspective are slightly different compared to critical parts from procurement or financial point of view.

1.2. PROJECT GOAL:

- To examine the multi-criteria classification methods of spare parts.
- To analyze the use of spare parts classification to improve the inventory strategy management.
- To investigate the spare parts classification methods to reduce the inventory cost.
- To propose a practical framework for management to improve the decision-making process-using spare parts classification.

1.3. RESEARCH METHODOLOGY

This research is intended to reduce maintenance cost by providing a systematic classification of spare parts criticality and support in management decision-making process. Therefore, the introduced method was be compared with current practice to justify the investment feasibility in the proposed approach while meeting the research goals.

Initially, an interview was conducted with the maintenance managers and procurement/logistics managers to understand the current practices and associated issues. These interviews helped in formulating the problem statement for this research and support its feasibility. Another interview is planned to discuss the expected impact of introducing and implementing a multi-criteria classification method on the current practices.

Additionally, a study visit to warehouse and stock holding units was done to obtain an overall view of current practices. Moreover, similar visits and interviews with local spare parts suppliers are conducted in order to provide a better understanding of their process and setup.

There are two types of data required for this research. The first is quantified data that have been collected from a company maintenance and planning system SAP such as unit price and annual demand. Additional data such as handling and ordering cost are available from a warehouse database. The second type of data is qualitative data that was collected by interviewing a focus group of subject matter experts "SMEs" to identify intangible aspects of the studied spare parts such as part impact, loss of production and type of maintenance adopted.

Due to the enormous number of items in a maintenance spare parts database, this project will focus only on spare parts that are related to rotating equipment. Since the qualitative and quantitative aspect needs to be considered, the analytic hierarchy process will be used as multi-criteria tools to help in identifying the spare parts criticality aspect. The outcome will be classified and analyzed using the vital, essential and desirable VED classification method.

1.4. REPORT OUTLINE

This section presents the basic structure of this research and briefly introduces its different chapters and sections. The next chapter will cover the Literature review to get the most relevant concepts and the most recent study on the subject of the researched areas.

The third chapter will provide information about the current industrial practice then will discuss the proposed approach. The fourth chapter we will be about the practical implementation of the proposed method. The final chapter will demonstrate the outcome of the result and summarize the research conclusion in addition to propose the recommendations.

CHAPTER 2: LITERATURE REVIEW

The research project started by conducting an extensive literature review in several books, academic research paper and in conference proceedings. This chapter will investigate the literature on the link between maintenance practices and spare parts management with focuses on the driving factors in the decisions making process for maintenance planning. After that, it is going to review the best practices methods and approaches adopted in the industry. The main keywords for research were Spare Parts, Spare Parts Classification, Maintenance Spare parts and Spare parts Criticality.

2.1 MAINTENANCE PRACTICES AND SPARE PARTS MANAGEMENT

There are two commonly adopted approaches in the industry when it comes to formulate maintenance and spare parts policies. Either by looking at maintenance and spare parts independently or combined. However, since maintenance activities drive the spare parts demand, it is more practical to approach both subjects simultaneously. Maintenance Management Handbook[1] define the spare parts management as the act of assuring the availability of required spare parts in the right quality and quantity at the right time at the minimum cost. However, maintenance organization is held accountable for most of this obligation, since the spare parts availability plays an essential role in supporting the effectiveness of maintenance programs.

According to Pintelon and Gelders [2], the objective of maintenance is to "maximize equipment availability in an operating condition permitting the desired output quantity and quality." Moreover, in the maintenance and inventory study by Van Horenbeek et al.[3] emphasize the logical and robust connection between maintenance and inventory control while indicating that the spare parts demand is a natural result driven by the failure based maintenance (also called corrective maintenance). On the other hand, during the part failure, the maintenance must react to replaced or repaired defective parts. In such event, the availability of spare parts will help to avoid production upset and reduce equipment downtime.

According to Al-Tarawneh [4], many theorists view decision-making as the fundamental managerial function. Deciding which parts to purchase when to purchase and how many units is considered a challenge in spare parts management. In fact, the decision-making process represents one of the crucial pillars in managing spare part. Therefore, managers dedicate a considerable amount of time and effort in order to come up with the most effective and efficient inventory policy.

2.2 SPARE PARTS CLASSIFICATION METHODS

The Classification methods have been extensively reviewed in the literature given that part classification could seem an easily solvable problem; the discussion available in the literature is a proof that there are more complications to be considered. Moreover, there are no one methods that fit all environment, but it is essential to understand the purpose of classification and identify the input criteria that are going to be analyzed by the proposed system.

The first stage of classification method is to define the classification input criteria. The research of Molenaers et al. [5] has selected four types of criteria extracted from four case studies they are lead time, the probability of item failure, number of potential suppliers and part cost. Moreover, the classification model presented by Flores and Whybark [6] use the traditional A, B or C ranking in two stages, start with rank the items based on criticality then ranks items based on part dollar value. A more comprehensive study by Bacchetti and Saccani [7] on 25 research papers showed the most commonly used criteria are part criticality, part cost, demand volume, supply characteristics and demand variability. A summary of Bacchetti is shown in Table [1]

Table [1]: Overview Of The Main Spare Parts Classification Contributes.
Source: Andrea Bacchetti, Nicola Saccani. 2012. Omega 40, 722-737.

Mono criteria	Multi-criteria	Classification criteria employed						Classification technique:				Application case			
								Quantitative		Qualitative		Case study with implementation	Case study as a test	Simulation	Absent
		Part cost/ value	Part criticality	Supply characteristics/ uncertainty	Demand volume/value	Demand variability	Others	ABC	Other	AHP	Other				
X					X			X				X			
X						X			X				X		
	X	X	X					X							X
	X		X		X			X					X		
	X					X	X Part reliability, Life cycle phase		X						X
	X	X	X	X		X			X				X		
	X	X	X		X		X Part weight, Repair efficiency		X						X
X			X							X			X		
	X	X		X					X			X			
	X	X	X			X	X Part specificity				X			X	
	X	X	X	X	X		X Life cycle phase			X			X		
	X	X		X	X			X					X		
	X	X	X	X	X					X			X		
	X			X		X			X			X			
	X					X			X					X	
	X	X	X	X	X			X						X	
	X	X	X	X	X			X						X	
	X	X		X	X			X						X	
	X					X			X			X			
	X	X	X	X		X	X Part specificity				X				
	X		X	X	X			X					X		
	X	X	X					X					X		
	X	X	X		X				X				X		
X					X			X				X			
	X	X	X	X	X		X Life cycle phase				X	X			

Very interesting criteria is the part criticality spare parts that also proposed by Naylor [8], the part criticality is a direct approach to classify the spare parts where a simple Low, Medium and High criticality are commonly adopted. The study of Huiskonen [9] divided the spare parts criticality into two categories. The first is the process criticality, which is driven by the consequences of the unavailable of the required spare parts and it is related to factors such safety, environmental or production loss. The second is the control criticality that related to factors such lead time, a variety of suppliers, part life cycle, costs, type of materials.

After identifying the proper input criteria concerning the criticality, the succeeding step is finding the suitable method to process those input. In the literature, many practices were observed ranging from quantitative methods and qualitative methods to using single criteria or multiple criteria spare parts classification methods. In the study of Partovi and Burton [10], they consider the use the Analytic Hierarchy Process (AHP) "introduced by Saaty [11] in 1988" as a method that has a practical comparison approach for weighing a combination of quantitative and qualitative criteria. Through the relative significance of various influencing factors and creates a structure for a complex system of multiple attributes.

However, Gajpal and Ganesh [12] proposed a new approach to combine the use of AHP along with VED defining three groups of spare parts (vital, essential and desirable).

On the other hand, qualitative methods to rank the importance of spare parts will require the input from experts, this input mostly will be based on experience and expert opinion, and defiantly it will be driven by the subjective judgments.

To overcome the subjective judgments using VED, this approach might be combined with another classification method. Gajpal et al. [13] propose to join the use of the Analytic Hierarchic Process with VED classification model. In addition, Sharaf and Helmy [14], proposed the same concept by considering five criteria and four sub-criteria to determining four groups of spare parts: vital, essential, important, and desirable.

2.3 SUMMARY

The number of study and research that cover the subject of the spare part indicated the importance of this subject. The maintenance management has excellent opportunity to improve the current practices and reduces cost. The reason why such studies are not wildly implemented in the industry, because field team can not understand most approaches. To overcome this more simplified method could adopt.

CHAPTER 3: RESEARCH METHODOLOGY: SPAR PARTS CLASSIFICATIONS

The first part of this chapter will be a review of the spare parts management current practices in the studied oil and gas operating company. This review focus on the classification methods and the stakeholders' decision-making process. After that, in the second part will describe how to construct a practical, systematic approach to overcome the deficiency in the current practices.

3.1 CURRENT PRACTICE:

The evaluation started by identifying all stakeholders in spare parts workflow figure [1]. Then select only the key stakeholders whom they regularly contribute to the decision-making process. The evaluation identifies three key stakeholders that playing a crucial role in the workflow.

The first stakeholder found to be the maintenance group. This team includes technicians, supervisor and maintenance planner. The second stockholder is a material group; this includes material coordinator and warehouse team and inventory coordinator. The third stakeholder is procurements group; this group covers the buyers and expediter officers. By observing the three groups, the verity between them was apparently noticeable in how they are approaching the spare parts management where each adopts their strategy of classification, and each team has their techniques in addressing the spare part decision making.

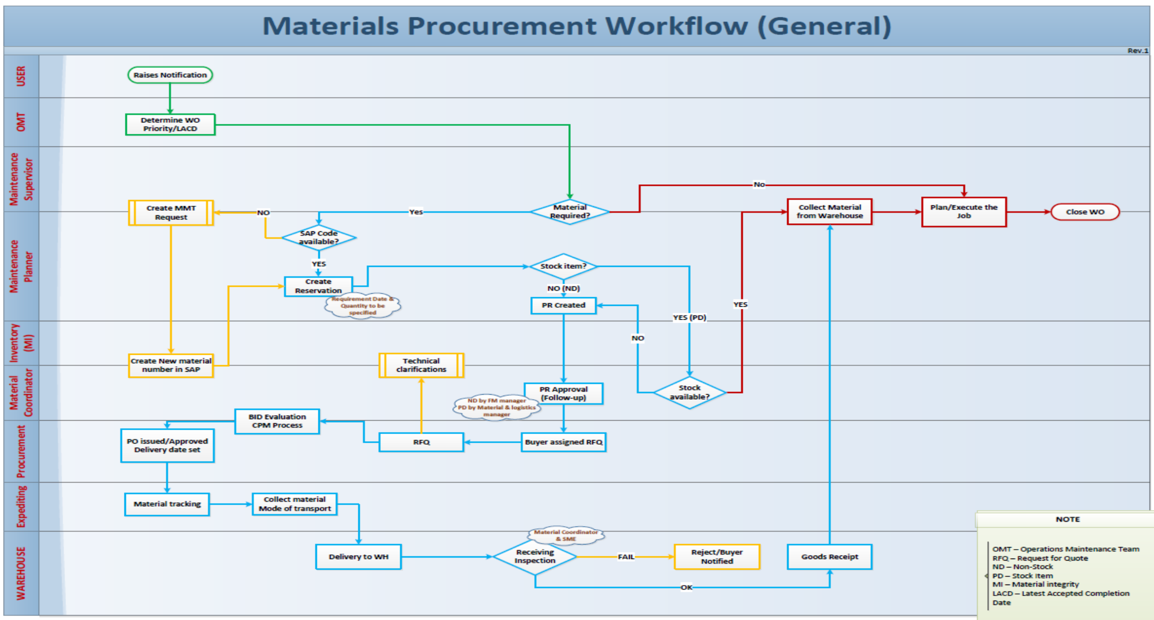

Figure [1]: Material Procurement Workflow

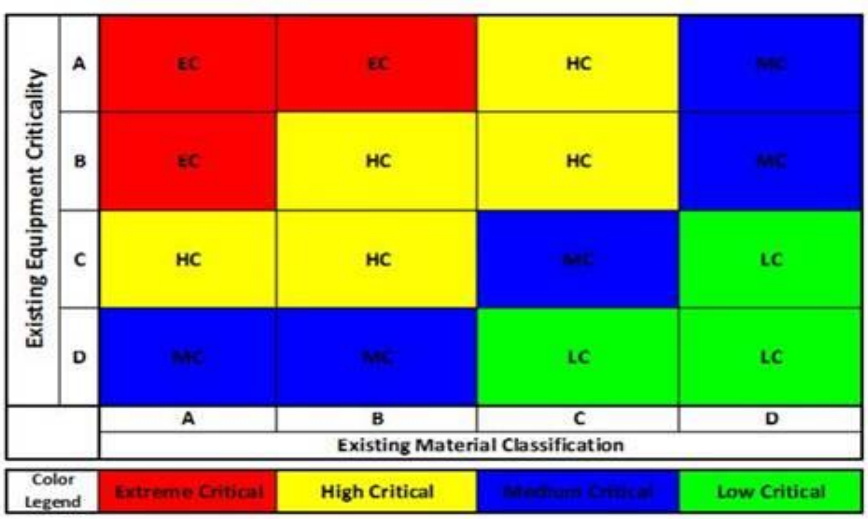

Figure [2]: Maintenance Classification Matrixes

The maintenance group uses criticality matrixes to classify the spare part Figure [2]. This strategy looks at the machine as one unit. That mean, if the machine is classified as critical for the facility operations, then all parts listed in the bill of material is considered critical. Also, they are using ABCD ranking for the level classification, where A is the most critical part, and D is the least. On the other hand, the material group is less concern with the parts classification. They are mostly looking for the priority input from maintenance team, although, they concierge about material lead time if it is for the critical machine and required a long time to be available at the site in this case this item will get more attention. However, as noticed there is no clear classification strategy adopted by the material group. Finally, the procurements group is more concern about the cost of the pasts and any additional cost added to the purchases order such as transportation cost “air, land or sea” or any special handling costs.

3.2 ISSUES AND GAPS IN THE CURRENT PRACTICES

The first issue with the previous practice was the evident disengagement between the teams and lack of holistically approach towards the spare parts management. Since each team has their own strategy that level of attention and interest will not be this same at each phase of the workflow. Also, this gab might cause a conflict and disagreement, especially between maintenance and procurement team since each has worked under different priority and with, unlike justifications. The second issue is the link between the criticality of the machine and the listed spare parts for that specific machine. This approach caused the stocking of a massive number of spare parts even though most of these parts does not have any effect on the machine operation. This practice will inquire; an avoidable inventory cost for non-critical parts and thus might lead to obsolescence risk. The last issue and the most important one, the criticality classification methods is considered using a single factor. This factor will solely determine the classification level of the past. The issue with such approach is that the single factor will not reflect the general criticality of the spare part and will exclude the other features that contributed in forming of the spare part.

Table [2]: Current Practice Classification

Group	Classification Factor	Description
Maintenance	Machine Criticality	- A: Extremely Critical - B: Highly Critical - C: Moderately Critical - D: Low Critical
Material	Lead- Time	- Long: Over 60 Days - Medium: from 30 to 60 Days - Short: Less than 30 Days
Procurements	Purchasing Cost	- More than $5000/unit - $500-$5000/unit - Less than $500/unit

3.3 PROPOSED METHODS

3.3.1 CLASSIFICATION OF SPARE PARTS

As have been seen in previous part the issue of adopting single criteria spare parts classification approaches which opens the door for enhancement opportunity that could have a significant improvement in the effectiveness of spare parts management imitative.

Adopting a multiple criteria framework to determine the parts criticality classification might help in providing a more accurate and reliable spare parts management decisions. The proposed system consisted of three main parts: Input – Process – Output. Where desirable output from the system is to determine the criticality level of the examined spare parts which will drive the spare parts management decision. To achieve the output goal, an appropriate input must be entered into the system. Moreover, aspects such as data availability and applicability of the input data must be satisfied which indicate the importance of identifying the proper input that is the spare parts criteria. Referring to the literature and subject matters expert SMEs opinion, in this project, four primary spare parts criteria for classification are considered as useable input to the system, they are machine impact, part price, lead-time, and demand frequency. The importance of each criteria for spare parts classification is briefly discussed next.

The machine impact criteria describe the parts that have direct or indirect effect on the machine operations. Even though this criteria has a definite impact, but it is the most difficult to identify. In this research, after consulting with the maintenance and engineering experts it was agreed about only two states in case of parts failure, is it going to stop the machine or it does not. The part cost criteria describe the cost of buying the parts. The lead time criteria describe the time between issuing the purchasing request to the supplier and delivering it to the site. The demand frequency criteria describe the number of units expected to be consumed in a specific period of time. Part cost, lead time and demand frequency are available in the maintenance and planning systems such SAP.

3.3.2 CALCULATING THE AHP SCORE

The part criticality is shaped by the specific factors that form the neuter of the spare parts. To use the four identified criteria to determine the part criticality score, a weighting metric need to be developed to rank the importance of each criteria. Since qualitative and quantities data are going to be evaluated, a proper tools required to be used to satisfy this data variation. Moreover, to identify the relevant weight of importance for each criteria, a pairwise comparison would be constructive to understand the tradeoff between criteria. As have been highlighted in the literature review, the best in the class tool to identify the relative weight for a different type of factor is the Analytic Hierarchy Process (AHP), developed by Satty [X]. AHP is a multi-criteria decision making structured technique for comparing and weighing complex factors where both qualitative and quantities aspect need to be considered.

Using of the AHP required decomposing of the evaluated criteria into a hierarchy of comprehended sub-criteria, each of which can be analyzed independently. The hierarchy structure below showed the four primary criteria and the sub-criteria for each primary criteria. The sub-criteria are obtained from the interviews with the three identified key stakeholders and by analyzing the spare parts in a database system.

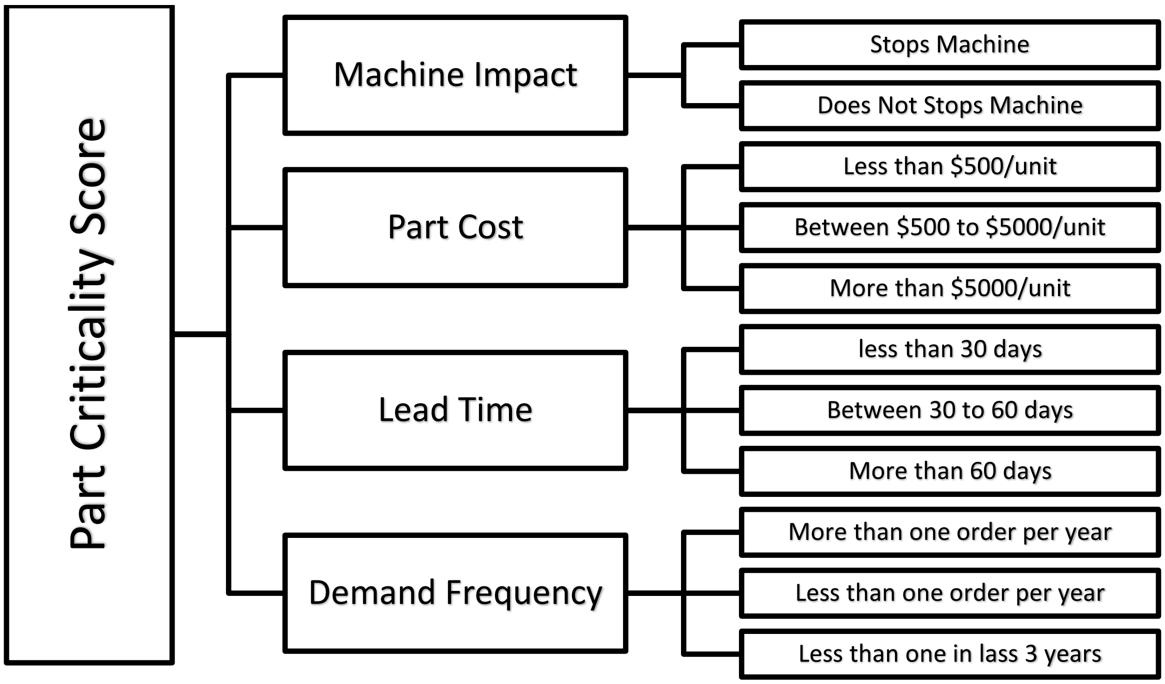

Figure 3: Spare Parts Criteria Analytic Hierarchy

As soon as the primary criteria and sub-criteria clearly identify the AHP pairwise, comparisons used to reveal SMEs preferences on these criteria when they are ranking the criticality of each spare part importance.

Table 3: AHP Scale for Pairwise Comparisons

Importance	Definition	Explanation
1	Equal importance	Element *A* and *B* contribute equally to the Criteria
3	Moderately Important	Slightly favor Criteria *A* over *B*
5	Strongly Important	Strongly favor Criteria *A* over *B*
7	Very Strongly Important	Criteria *A* is favored very strongly over *B*
9	Extremely Important	Favoring Criteria over *A* over *B* is of the highest possible order of importance
2, 4, 6, 8	Intermediate values	When compromise is needed. For example, 4 can be used for the intermediate value between 3 and 5

To explain what pairwise comparison lets take the following example. Suppose it is required to show preference between two type of fruits, for example, Apple and Banana. In this case, the question will be which fruit you like more than the other and in comparison with the other how much you like it. Let us make a relative scale to measure how much you like the fruit on the left (Apple) compared to the fruit on the right (Banana). If you like the apple more than banana, mark a number between 1 and 9 on the left side, while if you favor banana more than apple, then you mark on the right side. For instance, I strongly favor banana to apple then I give mark like it is done in Figure 4.

Option A 	Extremely Important	Very Strongly Important	Strongly Important	Moderately Important	Equally Important	Moderately Important	Strongly Important	Very Strongly Important	Extremely Important	Option B 
	9	7	5	3	1	3	5	7	9	
Apple	☐	☐	☒	☐	☐	☐	☐	☐	☐	Banana

Figure 4: Example of AHP Pairwise Comparison

For this project If expert thinks the Criteria ‘Machine Impact’ in column A is strongly more important than the option ‘Part Cost’ in column B, then mark 5 on the left-hand side. On the other hands if an expert thinks the option ‘Demand Frequency' in column B is extremely more important than the option ‘Machine Impact’ in column A, then mark 9 with (X) on the right-hand side.

With respect to **Primary Criteria**										
Option A	Extremely Important	Very Strongly Important	Strongly Important	Moderately Important	Equally Important	Moderately Important	Strongly Important	Very Strongly Important	Extremely Important	Option B
	9	7	5	3	1	3	5	7	9	
Machine Impact	☐	☐	☒	☐	☐	☐	☐	☐	☐	Part Cost
Machine Impact	☐	☐	☐	☐	☐	☐	☐	☐	☒	Demand Frequency

Figure 5: Example for AHP Primary Criteria Pairwise Comparison

An AHP questionnaire has been distributed to 9 experts whom they have a direct relationship to the spare part management decision. The experts come from deferent backgrounds such as maintenance, material planning specialists and facility support engineer. The feedback was collected independently to avoid bias judgment and reduce group thinking

With respect to **Primary Criteria**, Using the scale from 1 to 9 (where 9 is extremely and 1 is equally important), please indicate (X) the relative importance of options A (left column) to options B (right column).																		
A Options	Extremely Important		Very Strongly Important		Strongly Important		Moderately Important		Equally Important		Moderately Important		Strongly Important		Very Strongly Important		Extremely Important	B Options
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Machine Impact	○	○	○	○	◉	○	○	○	○	○	○	○	○	○	○	○	○	Part Cost
Machine Impact	◉	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Demand Frequency
Machine Impact	◉	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Lead Time
Part Cost	○	○	○	○	○	○	○	○	◉	○	○	○	○	○	○	○	○	Demand Frequency
Part Cost	○	○	○	○	○	○	○	○	◉	○	○	○	○	○	○	○	○	Lead Time
Demand Frequency	○	○	○	○	○	○	○	○	◉	○	○	○	○	○	○	○	○	Lead Time

Figure 6: Feedback Sample

While analyzing the expert feedback, an important aspect needs to be checked which is the consistency of the feedbacks. As per Satty, the inconsistency is inherited in the judgment process. The inconsistency feedback could indicate an error in the measurement or less coherent feedback. The following example will explain the concept of inconsistency feedback. For this project, if expert identify the Primary Criteria 'Machine Impact' as extremely more important than 'Part Cost,' then the same expert identify 'Part Cost' is extremely more important than 'Lead Time,' for consistency the 'Machine Impact' must be identified as extremely more important than 'Lead Time.' For this reason, each feedback has been checked for inconsistency and corrected.

The next step is to arrange the feedback for each criteria pairwise comparison then ., Figure [7]. The resulted computation that represented in percentage value, combining the result of each group will add up to a total of 100%. Table [4] illustrates the combined and normalized feedback from all experts for the primary criteria the last column to the right shows the weighted average for all feedback.

Decision Matrix

	1	2	3	4
1	1	5.00	9.00	9.00
2	0.20	1	1.00	1.00
3	0.11	1.00	1	1.00
4	0.11	1.00	1.00	1

Number of comparisons = 6
Consistency Ratio CR = 1.6%

Criticality Weight

	Criteria	Weight	Rank
1	Machine Impact	71.2%	1
2	Part Cost	10.6%	2
3	Demand Frequency	9.1%	3
4	Lead Time	9.1%	3

Figure [7] : Pairwise Analysis Result For The Primary Criteria For One Feedback

Table 4: Criteria Pairwise Comparison Compute and Normalize

	Category	**FB 1**	**FB 2**	**FB 3**	**FB 4**	**FB 5**	**FB 6**	**FB 7**	**FB 8**	**FB 9**	**Avgas**
1	Machine Impact	59%	65%	56%	68%	62%	51%	71%	74%	61%	63%
2	Part Cost	6%	11%	8%	4%	14%	7%	11%	5%	4%	8%
3	Demand Frq.	16%	9%	29%	19%	20%	27%	9%	13%	10%	17%
4	Lead Time	19%	15%	7%	9%	5%	16%	9%	9%	25%	12%
	Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Table 5: Primer Criteria Criticality Ranking

	Category	**FB 1**	**FB 2**	**FB 3**	**FB 4**	**FB 5**	**FB 6**	**FB 7**	**FB 8**	**FB 9**
1	Machine Impact	1	1	1	1	1	1	1	1	1
2	Part Cost	4	3	3	4	3	4	2	4	4
3	Demand Frq.	3	4	2	2	2	2	3	2	3
4	Lead Time	2	2	4	3	4	3	3	3	2

It is clear that machine impact ranked as the most critical criteria by all experts Table [5]. This outcome has reasonable justification especially in the company where the revenue is highly depending on production and production depending on machine operations. On the other hand, the expert response has very for the remaining criteria. The Demand Frequency has been ranked as the second priority by 5 experts' feedbacks. The third priority was for the Lead Time, which was ranked by 4 experts' feedbacks. The least priority to be the Part Cost was indicate by 5 experts' feedbacks. This ranking result is also matching the average weighted from all feedbacks. As shown in Table [4], the machine impact has criticality weight of 63% and the Demand Frequency, Lead Time and Part Cost are weighted 17% 12% 8%.

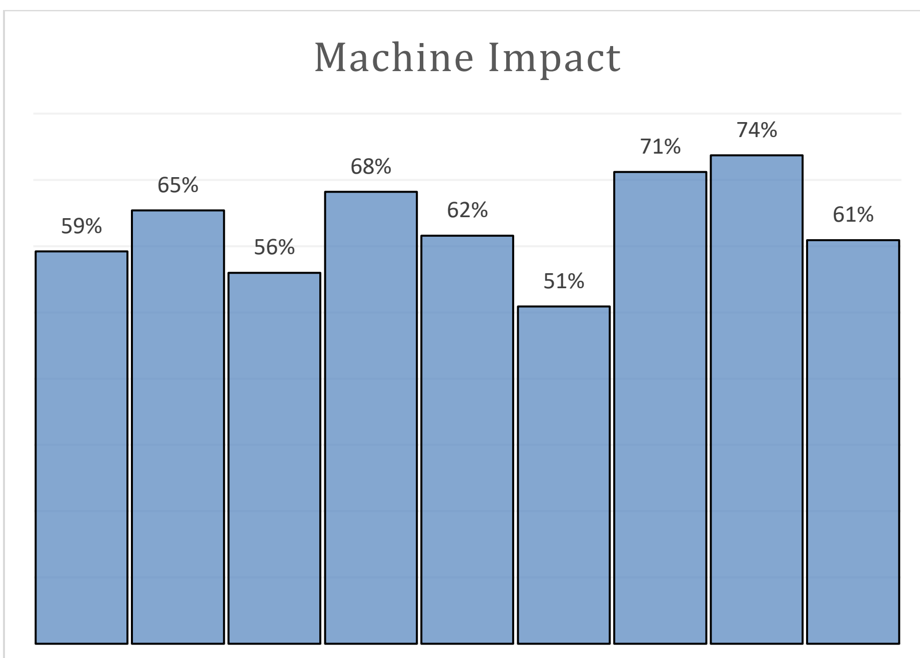

Figure [8]: Individual SME Ranking For Machine Impact

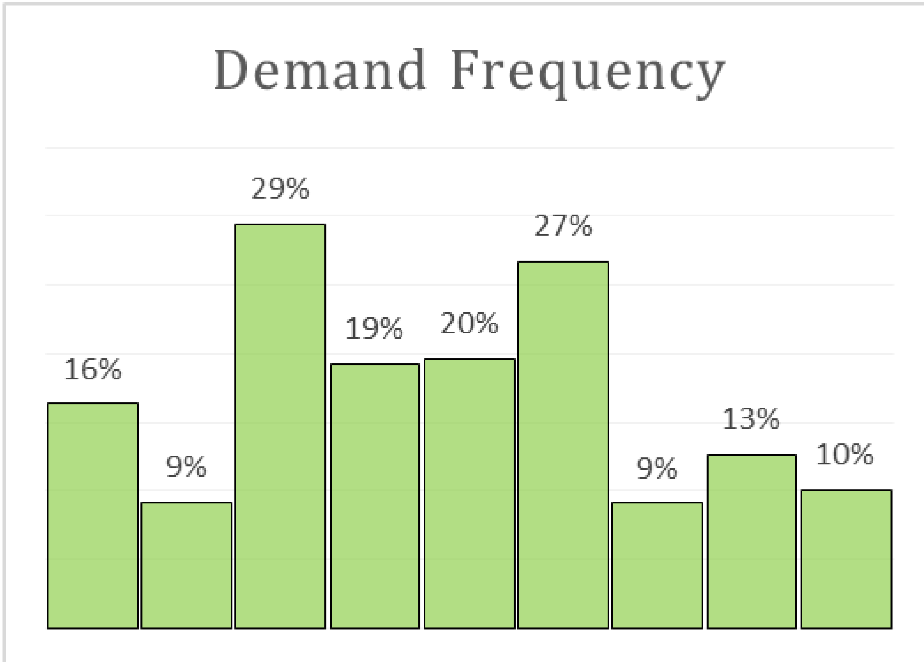

Figure [9]: Individual SME Ranking For Demand Frequency

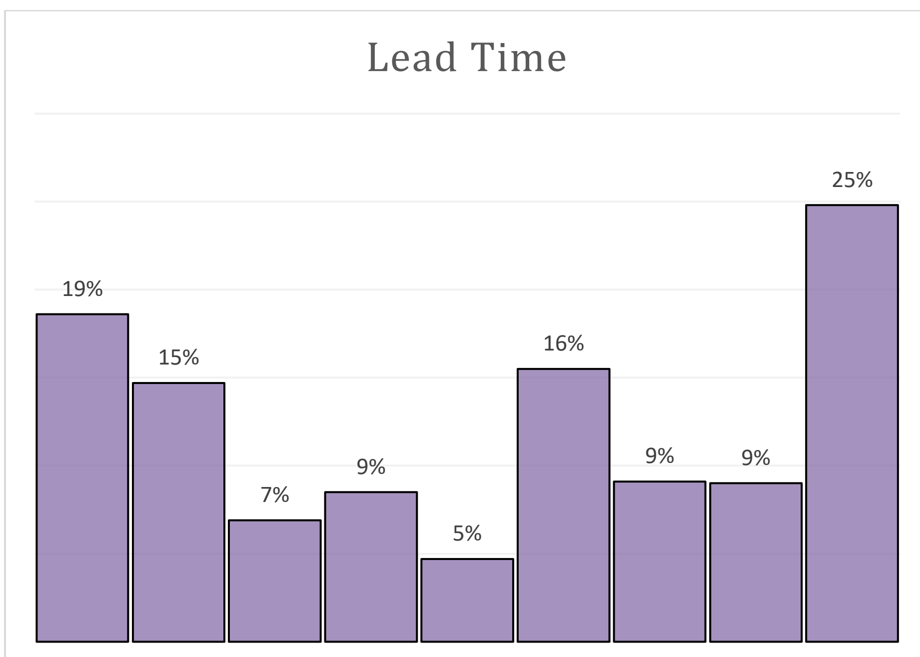

Figure [10]: Individual SME Ranking For Lead Time

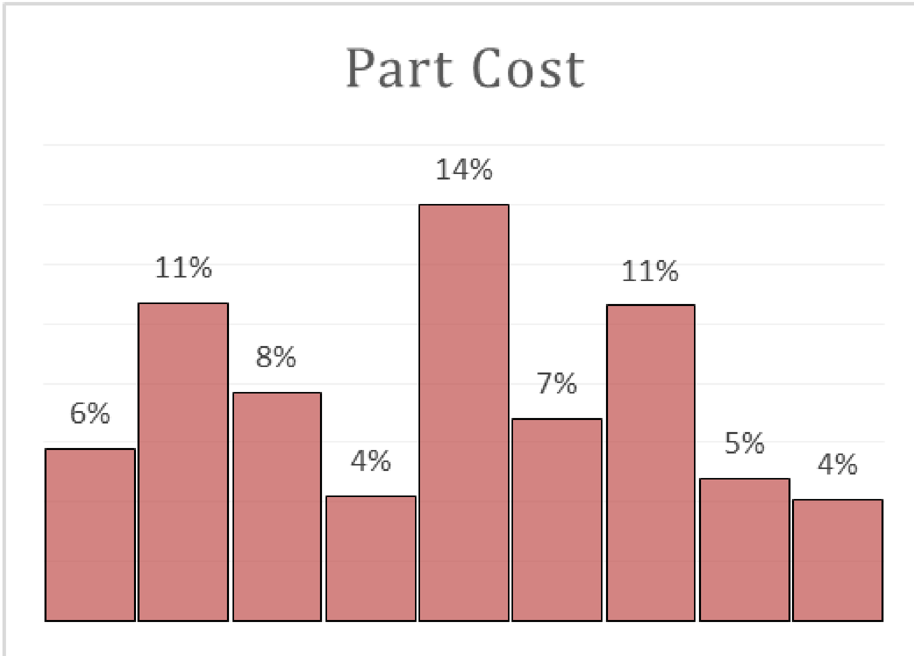

Figure [11]: Individual SME Ranking For Part Cost

The same process is applied to the sub-criteria for each primary criteria. The Table [6] shows the combined and normalized feedback from all experts for the sub-criteria for each primary criteria. The machine impacted has the advantage of sub-criteria importance for the part that could stop the machine over the part that dose to stop the machine. For demand frequency, the most important sub-criteria is for the part that has demanded of more than one time per year. For the lead time, the important scale leans toward the part that has a lead time of more than 60 days. Finally, for the parts cost, all expert has identified that the high-cost part is more important than the medium and low-cost part.

Table 6: Overall Pairwise Comparison Compute and Normalize

		Category	Weight	Rank
Primary Criteria	1	Machine Impact	63%	1
	2	Part Cost	8%	4
	3	Demand Frequency	17%	3
	4	Lead Time	12%	2
Machine Impact	1	Stops Machine	80%	1
	2	Does Not Stops Machine	20%	2
Part Cost	1	More than $5000/unit	62%	1
	2	$500-$5000/unit	25%	2
	3	Less than $500/unit	13%	3
Demand Frequency	1	More than one Order/year	57%	1
	2	less than one Order/year	31%	2
	3	No order in the last three years	12%	3
Lead Time	1	More than 60 days	58%	1
	2	30 to 60 days	27%	2
	3	Less than 30 days	15%	3

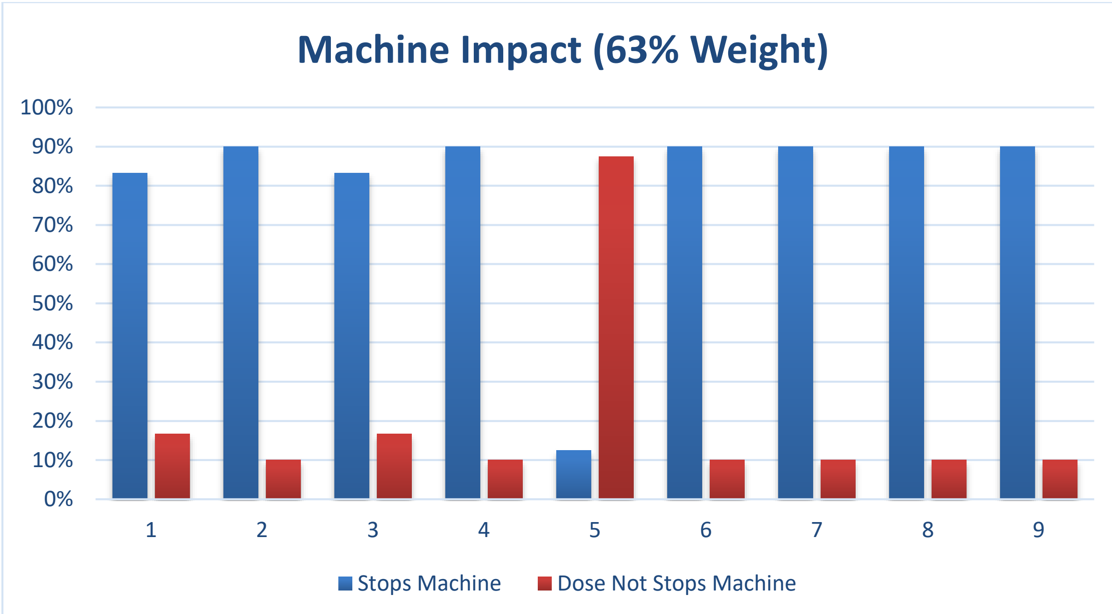

Figure [12]: Collective SME Ranking For Machine Impact

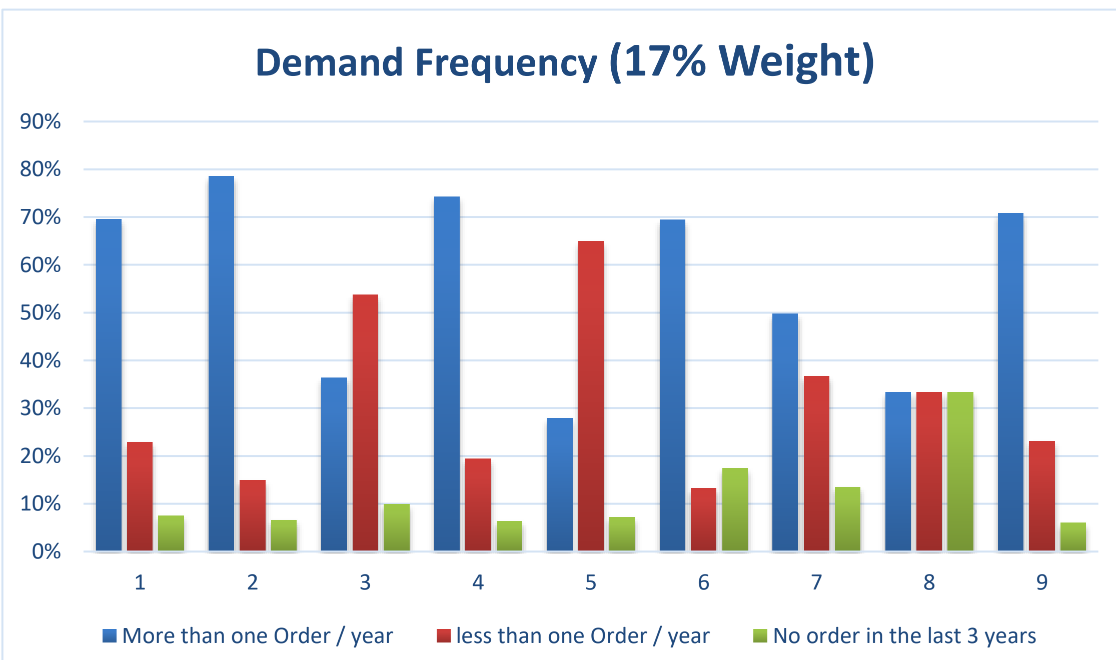

Figure [13]: Collective SME Ranking For Demand Frequency

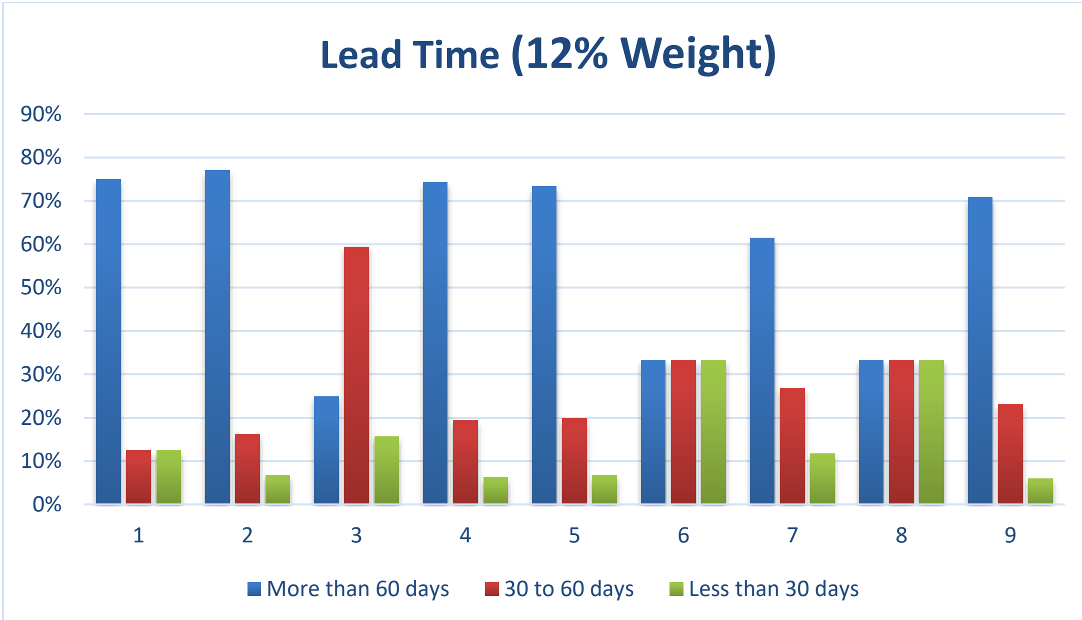

Figure [14]: Collective SME Ranking For Lead Time

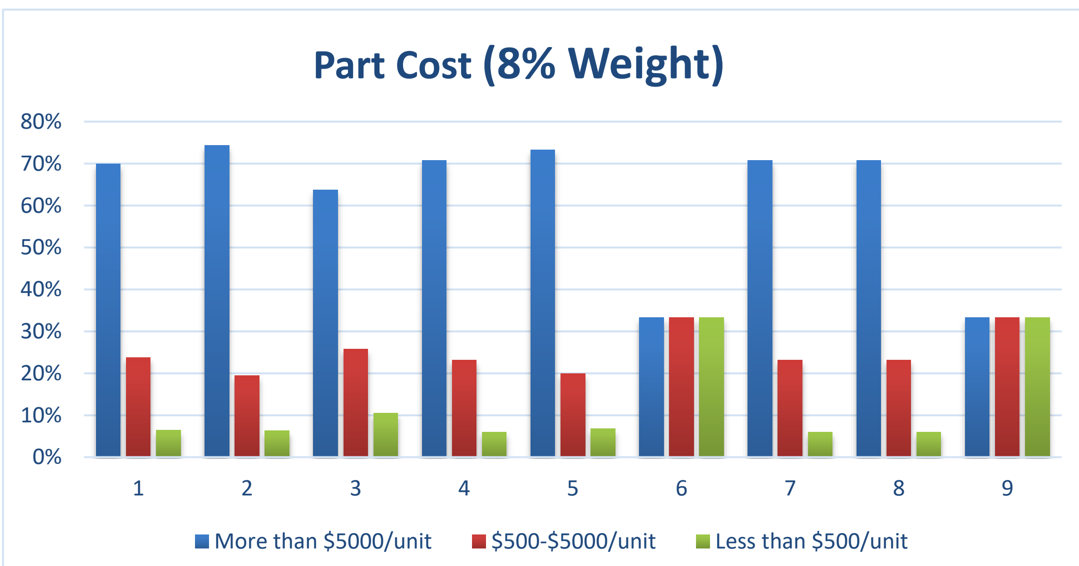

Figure [15]: Collective SME Ranking For Part Cost

To calculate the final weight, multiplied the importance percentage for sub-criteria is by the importance percentage of its primary criteria and repeated the same process for the other sub-criteria. The resulted number is then added to come up with the final part criticality score. To explain this step, assume we have a spare part A. This part will stop the machine in case of failure. This part cost 2000$ and required 15 days to arrive at the site after placing the purchase order. This part has an average demand of three times per year. Table [7] shows the final calculation of part criticality score PCS.

Table [7]: Example for Calculating Part Criticality Score

		Machine Impact	**Demand Frequency**	**Lead Time**	**Part Cost**
Spare part A		Yes	3 orders per year	15 days	2000
		Stops Machine	> one Order	< 30 days	$500-$5000/unit
	Criteria Weight	63%	17%	12%	8%
		*	*	*	*
	Sub Weight	80%	57%	15%	25%
		=	=	=	=
	Individual Score	50.4%	9.7%	1.8%	2%
	PCS	**64%**			

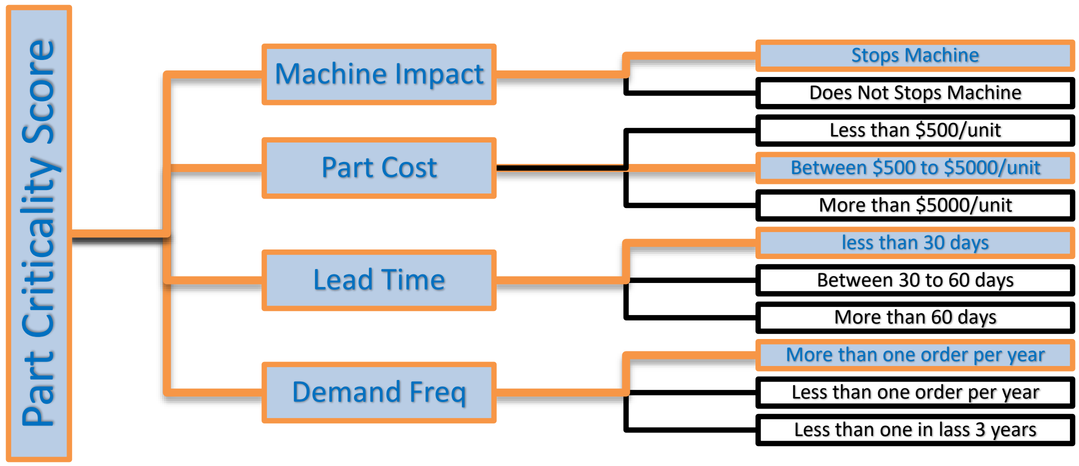

Figure 16: Spare Parts Criteria Hierarchy

3.3.3 FINDING THE PART CRITICALITY CLASSIFICATION

At this stage, a criticality score can be easily calculated for any spare part using the steps mentioned in pervious part. However, this criticality scores still not practical to be used directly to classify the parts and in need some enhancement to make it more practical useful tools. The next step is to define the boundary conditions for the usage of the criticality score. The rustle of this project is a spectrum of the score from 17% to 72% determined from different combinations of the sub-criteria. The highest score of 72% result from a part that stops the machine if not available, with demand frequency of more than once each year, its lead time is more than 60 days and costs more than 5000$ per part. On the other hand, the lowest score of 17% result from a part that does not stop the machine if not available, has no order in the last three years while its lead time is less than 30 days and costs less than 500$ per part.

To make practical use of the scoring approach in the previous part, an additional classification system is used to consolidate with the Vital-Essential-Desirable VED classification system to have more relevance to the user of this criticality score. The VED classification system is wildly used in the spare parts management. To relate each class to the AHP criticality score each class of VED is defined as follow:

Desirable spare parts consist of parts whose function does not have a significant impact on the quantity or quality of manufactured products. Therefore, it can allow the equipment to be some time out of service. Consequently, the parts are considered desirable if does not stop the machine while the part annual demand, lead time and cost have no direct impact on this classification. The low limit for desirable can be identified from the lower boundary determine using the criticality score that was 17%.

Vital spare part is parts, if not available will cause immediate and expensive downtime, and an unacceptable decrease in the efficiency of the entire production process, and an unacceptable decrease in quality of products. Consequently, the parts considered vital if it stops the machine in case of failure. Besides, the longer the unavailability, the more accumulative cost and this related to the parts that have long lead time no matter what is the annual demand or part cost. The upper limit for desirable can be identified from the upper boundary determine using the criticality score that was 72%.

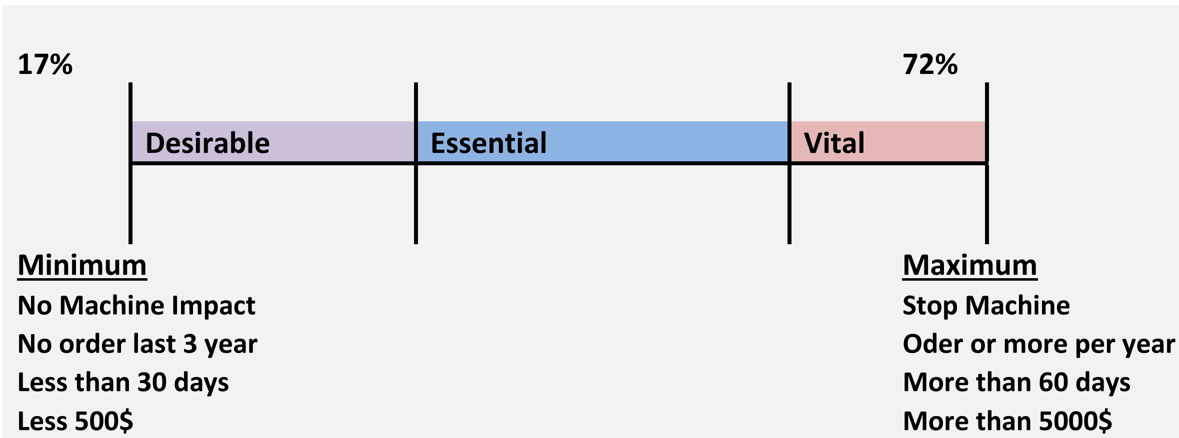

Figure [17]: System Boundaries

Essential spare part is parts if not available will leads to a significant loss of production, but will not interrupt the entire production process. This category left to the end because it falls between the other two categories. To determine the boundary for this category, first the upper limit will involve machine stops since it is at the edge with the vital category and the lower limit will involve the not affect the machine operations since it is the edge with desirable. Moreover, the criteria that play a role and need to be evaluated are lead time and the demand frequency. If the part is going to stop the machine and take a long time to replenish, combined with being likely to fail again shortly, then it should be Vital. Given these definitions, cut-offs can be established for the AHP criticality score, and distributions of spare parts can be examined. The table [8] and figure [18] illustrates this approach.

Table [8]: Classification Boundaries and Criteria Involvement

Category		Score	Descriptions
Desirable	Lower Limit	**17%**	No Machine Impact No order last 3 year Less than 30 days Less 500$
Essential	Lower Cutoff	**34%**	No Machine Impact Oder or more per year More than 60 days More than 5000$
	Upper Cutoff	**64%**	Stop machine Less than order year Between 31-60 days More than 5000$
Vital	Upper Limit	**72%**	Stop Machine Oder or more per year More than 60 days More than 5000$

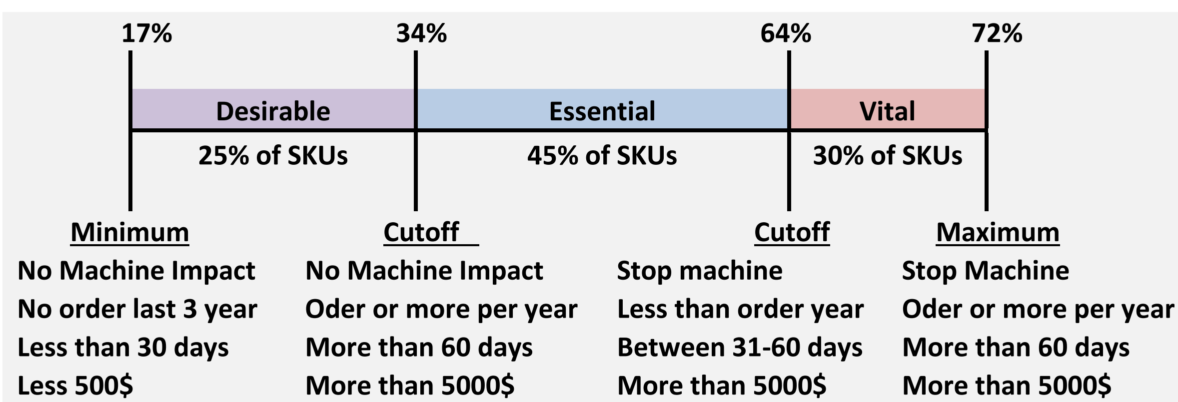

Figure 18: Classification Boundaries

3.4 SUMMARY

The adopted practices in the studied company have shown a noticeable variation in applying spare parts strategies between stakeholders in the materials workflow. However, most strategies lake a systematic approach in order to come up with accurate spare parts criticality classification. The proposed methods of using the AHP along with VED to evaluate the spare parts presented a practical and more accurate approach to classifying the criticality of the spare parts. This classification will help in the structuring of more unify spare parts police across all stakeholders.

CHAPTER 4: IMPLANTATION

To study the proposed system prior to the industrial implementation of the outlined classification and stock recommendations, classification model was developed and tested at a pilot site within the maintenance department. This chapter will review the proposed methods' inputs and outputs. A pilot evaluation conducted on a set of randomly selected spare parts. The following section will demonstrate the evaluation process from the Input to the final output.

4.1 DATA COLLECTION

There are two groups of data in this project. The first is the data that are going to be used to construct the evaluation methods that have been discussed in province chapter. Those data include the spare parts criteria and sub-criteria that is going to be evaluated using AHP. Those data coming from two sources the first is the company database system such as SAP and in-house material inventory system. Those systems are a reliable source for quantities data where data can be collected faster and more accurate. The second source of data is the interviews with subject matter experts where they will provide the qualitative data that rarely available in the system such SAP.

The second group of data is the ones that are going to be evaluated by using the methods devolved in the previous chapter, and they are mainly the spare parts information. The most reliable sources for these data are company database system such as SAP and in-house material inventory system in addition to spare parts suppliers. For this pilot, a list of 50 randomly selected spare parts.

A	A	B	C	D	E	F	G
#	Part Name	Part Number	Part Description	Machine Impact	Part Cost	Demand Frequency	Lead Time
1	AA	123	Electrical	Stops Machine	$500-$5000/unit	+1 per year	31-60 days
2	LIN Cards		Electrical Control	Stops Machine	$500-$5000/unit	+1 per year	>60 days
3	CIO Card		Electrical Control	Stops Machine	$500-$5000/unit	+1 per year	>60 days
4	PEC 800		Electrical Control	Stops Machine	$500-$5000/unit	no order last 3 year	>60 days
5	UV Relay for ASI VFD		Relay	Stops Machine	$500-$5000/unit	+1 per year	>60 days
6	Relay Power Module		Relay	Does Not Stops Machine	<$500/unit	+1 per year	>60 days
7	ASI Power Modules		Electrical	Stops Machine	>$5000/unit	+1 per year	>60 days
8	ASI VFD Capacitors		Electrical	Stops Machine	$500-$5000/unit	<1 per year	>60 days
9	Toshiba VFD Capacitors		Electrical	Stops Machine	$500-$5000/unit	<1 per year	>60 days
10	Light Bulbs		Electrical	Does Not Stops Machine	<$500/unit	+1 per year	
11	ABB Thyristors		Electrical	Stops Machine	>$5000/unit	<1 per year	>60 days
12	EVFD Power cells		Electrical	Stops Machine	$500-$5000/unit	+1 per year	>60 days
13	EVFD Fiber Optics Cable		Electrical Protection	Stops Machine	$500-$5000/unit	<1 per year	>60 days
14	FGSU Rectirifers		Electrical	Does Not Stops Machine	<$500/unit	no order last 3 year	>60 days
15	Ballast 2x36W		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	<30 days
16	Multimeter		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days
17	6V crane remote control battery		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days
18	Diode Front end module ASI		Eletrical	Stops Machine	>$5000/unit	<1 per year	>60 days
19	Inductor filter ASI		Eletrical	Stops Machine	>$5000/unit	<1 per year	>60 days
20	XLPE power cable (LV, 3C, many size)		Eletrical	Stops Machine	$500-$5000/unit	+1 per year	31-60 days
21	XLPE control cable (LV, many size and core0		Eletrical	Stops Machine	$500-$5000/unit	+1 per year	31-60 days
22	COPASLIP AEROSOL		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	31-60 days
23	LAMP fitting 2x18W		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	31-60 days
24	Lamp fitting 2x36 W		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	31-60 days
25	Gloves cut resistant		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days
26	Aviation warning light 700W		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	31-60 days
27	Micro Ohm meter		Eletrical	Does Not Stops Machine	$500-$5000/unit	<1 per year	>60 days
28	High temperature wire, fiber glass		Eletrical	Stops Machine	$500-$5000/unit	+1 per year	>60 days
29	Crowbar stack ASI		Eletrical	Stops Machine	>$5000/unit		>60 days
30	CEAG local control station		Eletrical	Does Not Stops Machine	$500-$5000/unit	+1 per year	>60 days
31	Silica Gel		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days
32	Grease EP2		Eletrical	Stops Machine	<$500/unit	+1 per year	>60 days
33	240V DOL starter		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days
34	2x36W lamp		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days
35	Capacitor 32MFD italsmea		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days
36	Chiller units TRANE		Eletrical	Does Not Stops Machine	>$5000/unit	<1 per year	>60 days
37	Battery bank, Lead Acid, FIAMM		Eletrical	Does Not Stops Machine	>$5000/unit	+1 per year	>60 days
38	Signal lamp LCS		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days
39	400W lamp ignitor		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days
40	Cut resistant gloves		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	<30 days
41	Nytro Libra Transformer oil		Eletrical	Does Not Stops Machine	$500-$5000/unit	<1 per year	31-60 days
42	Alimak elevator safety device		Eletrical	Stops Machine	$500-$5000/unit	<1 per year	>60 days
43	UPS/BC cooling fan		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	31-60 days
44	Nuts/bolts/cable lugs (assorted)		Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	<30 days
45	Motor bearing (different size/shape)		Eletrical	Stops Machine	<$500/unit	+1 per year	<30 days
46	Belts (different size/shape)		HVAC	Stops Machine	<$500/unit	+1 per year	<30 days
47	Expansion valve		HVAC	Does Not Stops Machine	<$500/unit	+1 per year	>60 days
48	Blower fan motor		HVAC	Stops Machine	<$500/unit	+1 per year	<30 days
49	Refrigerant		HVAC	Does Not Stops Machine	<$500/unit	+1 per year	<30 days
50	Nitrogen		HVAC	Does Not Stops Machine	<$500/unit	+1 per year	<30 days

Figure [19]: Spare Parts List

4.2 PILOT IMPLEMENTATION

Due to the popularity of MS-Excel, the evaluated data has been entered into the spreadsheet, where calculation formula has been developed. Moreover, the experts from the studied company have revealed their preference for the use of MS-Excel. Figure [20] shows a screenshot from the spreadsheet where the user will enter information of the evaluated parts then select from the drop-down list the parts sub-criteria data. Then the developed formal will compute the part criticality score and identify the relative classification.

#	Part Name	Part Description	Lead Time	Lead Time	Lead Time	Lead Time	AHP Score	Part Classfication
1	AA	Electrical	Stops Machine	>$5000/unit	<1 per year	>60 days	68%	Vital
2	LIN Cards	Electrical Control Board	Stops Machine	$500-$5000/unit	<1 per year	<30 days	59%	Essential
3	CIO Card	Electrical Control Board	Does Not Stops Machine	>$5000/unit	no order last 3 year	<30 days	21%	Desirable
4	PEC 800	Electrical Control Board					#N/A	#N/A
5	UV Relay for ASI VFD	Relay					#N/A	#N/A
6	Relay Power Module	Relay	Stops Machine Does Not Stops Machine				#N/A	#N/A
7	ASI Power Modules	Electrical					#N/A	#N/A
8	ASI VFD Capacitors	Electrical					#N/A	#N/A
9	Toshiba VFD Capacitors	Electrical					#N/A	#N/A
10	Light Bulbs	Electrical					#N/A	#N/A

Figure 20: Screen Shot From the Spreadsheet

The majority of the input data can be easily extracted from SAP systems. For example, demand frequency is usually extracted from the work order history while the lead time and parts cost can be found from the most recent purchase order. On the other hand, for machine impact will not be explicitly available on the system, such qualitative data need to be manually identified by either assets engineering or maintenance team. However, this action is required once, and the system team would assign specific notifications to evaluated parts.

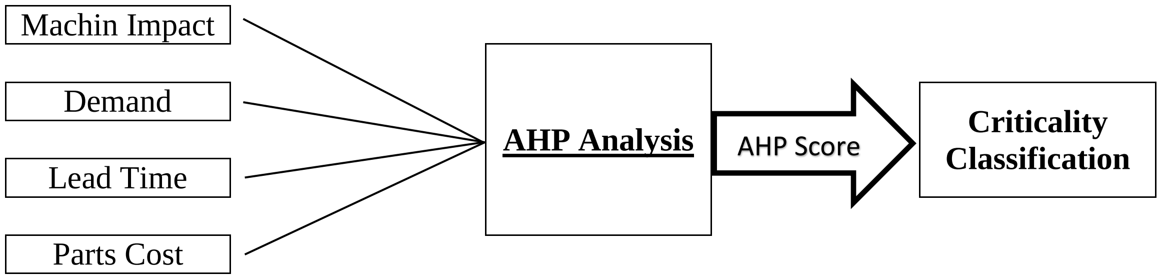

Figure 21: Ranking Process

4.3 RESULT EVALUATION

To test the outcome of the classification and to ensure the proposed system is reflecting a useable classification approach and could be utilized in the decision-making process. Two experts were provided with the input data and had been asked to come up with proper classification to the given list. The experts use only the input data and their judgment based on their experience. By comparing the two resulted, it has been noted that the accuracy of the tool showed a close match to the expert perspective. Even though, this may not reflect the reality since the tested sample is very small compared to the enormous number and variety of the spare parts database. However, the tools have proven its ability to provide a valuable unity framework not just for maintenance team but all other stakeholders in spare part management.

4.4 SUMMARY

The evaluation of the spare part sample shows the usefulness of the method in providing the required classification in very effective way. It was beneficial to compare the outcome of the proposed classification methods with assessment from the SME to check the trustworthiness and ensure tools are accurate enough to support the decision-making process. Figure [22] shows the complete list of evaluated spare parts list.

#	Part Name	Part Description	Lead Time	Lead Time	Lead Time	Lead Time	AHP Score	Part Classfication
1	AA	Electrical	Stops Machine	$500-$5000/unit	+1 per year	31-60 days	**65%**	**Vital**
2	LIN Cards	Electrical Control Board	Stops Machine	$500-$5000/unit	+1 per year	>60 days	**69%**	**Vital**
3	CIO Card	Electrical Control Board	Stops Machine	$500-$5000/unit	+1 per year	>60 days	**69%**	**Vital**
4	PEC 800	Electrical Control Board	Stops Machine	$500-$5000/unit	no order last 3 year	>60 days	**61%**	**Essential**
5	UV Relay for ASI VFD	Relay	Stops Machine	$500-$5000/unit	+1 per year	>60 days	**69%**	**Vital**
6	Relay Power Module	Relay	Does Not Stops Machine	<$500/unit	+1 per year	>60 days	**30%**	**Desirable**
7	ASI Power Modules	Electrical	Stops Machine	>$5000/unit	+1 per year	>60 days	**72%**	**Vital**
8	ASI VFD Capacitors	Electrical	Stops Machine	$500-$5000/unit	<1 per year	>60 days	**65%**	**Essential**
9	Toshiba VFD Capacitors	Electrical	Stops Machine	$500-$5000/unit	<1 per year	>60 days	**65%**	**Essential**
10	Light Bulbs	Electrical	Does Not Stops Machine	<$500/unit	+1 per year	<30 days	**25%**	**Desirable**
11	ABB Thyristors	Electrical	Stops Machine	>$5000/unit	<1 per year	>60 days	**68%**	**Vital**
12	EVFD Power cells	Electrical	Stops Machine	$500-$5000/unit	+1 per year	>60 days	**69%**	**Vital**
13	EVFD Fiber Optics Cable	Electrical Protection	Stops Machine	$500-$5000/unit	<1 per year	>60 days	**65%**	**Essential**
14	FGSU Rectirifers	Electrical	Does Not Stops Machine	<$500/unit	no order last 3 year	>60 days	**23%**	**Desirable**
15	Ballast 2x36W	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	<30 days	**25%**	**Desirable**
16	Multimeter	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days	**30%**	**Desirable**
17	6V crane remote control battery	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days	**30%**	**Desirable**
18	Diode Front end module ASI	Eletrical	Stops Machine	>$5000/unit	<1 per year	>60 days	**68%**	**Vital**
19	Inductor filter ASI	Eletrical	Stops Machine	>$5000/unit	<1 per year	>60 days	**68%**	**Vital**
20	XLPE power cable LV, 3C	Eletrical	Stops Machine	$500-$5000/unit	+1 per year	31-60 days	**65%**	**Vital**
21	XLPE control cable LV,	Eletrical	Stops Machine	$500-$5000/unit	+1 per year	31-60 days	**65%**	**Vital**
22	COPASLIP AEROSOL	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	31-60 days	**27%**	**Desirable**
23	LAMP fitting 2x18W	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	31-60 days	**27%**	**Desirable**
24	Lamp fitting 2x36 W	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	31-60 days	**27%**	**Desirable**
25	Gloves cut resistant	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days	**30%**	**Desirable**
26	Aviation warning light 700W	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	31-60 days	**27%**	**Desirable**
27	Micro Ohm meter	Eletrical	Does Not Stops Machine	$500-$5000/unit	<1 per year	>60 days	**27%**	**Desirable**
28	High temperature wire, fiber glass	Eletrical	Stops Machine	$500-$5000/unit	+1 per year	>60 days	**69%**	**Vital**
29	Crowbar stack ASI	Eletrical	Stops Machine	>$5000/unit	<1 per year	>60 days	**68%**	**Vital**
30	CEAG local control station	Eletrical	Does Not Stops Machine	$500-$5000/unit	+1 per year	>60 days	**31%**	**Desirable**
31	Silica Gel	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days	**30%**	**Desirable**
32	Grease EP2	Eletrical	Stops Machine	<$500/unit	+1 per year	>60 days	**68%**	**Vital**
33	240V DOL starter	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days	**30%**	**Desirable**
34	2x36W lamp	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days	**30%**	**Desirable**
35	Capacitor 32MFD italsmea	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days	**30%**	**Desirable**
36	Chiller units TRANE	Eletrical	Does Not Stops Machine	>$5000/unit	<1 per year	>60 days	**30%**	**Desirable**
37	Battery bank, Lead Acid, FIAMM	Eletrical	Does Not Stops Machine	>$5000/unit	+1 per year	>60 days	**34%**	**Desirable**
38	Signal lamp LCS	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days	**30%**	**Desirable**
39	400W lamp ignitor	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	>60 days	**30%**	**Desirable**
40	Cut resistant gloves	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	<30 days	**25%**	**Desirable**
41	Nytro Libra Transformer oil	Eletrical	Does Not Stops Machine	$500-$5000/unit	<1 per year	31-60 days	**23%**	**Desirable**
42	Alimak elevator safety device	Eletrical	Stops Machine	$500-$5000/unit	<1 per year	>60 days	**65%**	**Essential**
43	UPS/BC cooling fan	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	31-60 days	**27%**	**Desirable**
44	Nuts/bolts/cable lugs (assorted)	Eletrical	Does Not Stops Machine	<$500/unit	+1 per year	<30 days	**25%**	**Desirable**
45	Motor bearing (different size/shape)	Eletrical	Stops Machine	<$500/unit	+1 per year	<30 days	**63%**	**Essential**
46	Belts (different size/shape)	HVAC	Stops Machine	<$500/unit	+1 per year	<30 days	**63%**	**Essential**
47	Expansion valve	HVAC	Does Not Stops Machine	<$500/unit	+1 per year	>60 days	**30%**	**Desirable**
48	Blower fan motor	HVAC	Stops Machine	<$500/unit	+1 per year	<30 days	**63%**	**Essential**
49	Refrigerant	HVAC	Does Not Stops Machine	<$500/unit	+1 per year	<30 days	**25%**	**Desirable**
50	Nitrogen	HVAC	Does Not Stops Machine	<$500/unit	+1 per year	<30 days	**25%**	**Desirable**

Figure [22]: Complete List of Evaluated Spare Parts

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 PROJECT CONCLUSIONS

Spare part availability plays leading role in maintaining the facility operations and sustaining the continuance production. However, choosing the right strategy is considered a challenging task due to the quantity of information involved and the difficulties associated with collecting the required data. On the other hand, realizing the advantages form reducing the inventory expenditure,time and effort support its economic feasibility.

In this project, spare part classification framework is proposed to provide support and guide in the decision-making process. The framework uses multi-criteria classification that jointly evaluates qualitative and quantitative spare parts criteria aiming to determine the criticality classification of the examined spare parts. The outcome will be used to drive the spare parts management decision. The steps used to classify spare part can be summarized as follows:

1. Define the propose of the classification
2. Identify the primary criteria to be evaluated
3. Identify the sub-criteria to be evaluated
4. Use pairwise comparison to assign a proper metric weight for each criteria and sub-criteria
5. Calculate the completive weight for the evaluated part
6. Use the classification matric to determine the part classification

The proposed framework has been applied to a list of 50 spare items. The outcome classification was compared with the classification judgment of the subject matter expert. This result has indicted a very close match between both approaches. However, the use of the framework has the advantages of less time and can be performed by anyone.

In conclusion, this project proposes a practical and easy to use decision-making tools for spare parts classification management. The framework is validated for practical implementation. This study contributes towards a more comprehensive view of the spare parts management.

5.2 RECOMMENDATION AND FUTURE WORK

This project has shown the applicability of using the combined methods to improve the spare parts management. The proposed methods are powerful tools that can give the maintenance manager and supply manager an advantage in simplifying the complexity of managing spare parts. This framework can be programmed in the company ERP system in order to make it more automated. Moreover, this application can be improved by adding more criteria in the AHP analysis. This will provide better accuracy when evaluating and ranking the criticality spare parts. The future study could investigate the spare parts classification along with the spare part forecasting and would be the effect on the inventory stocking policy.

REFERENCES

[1] D. Palmer, Maintenance planning and scheduling handbook, 3rd edition, New York: McGraw-Hill, 2013.

[2] A. Molenaers, H. Baets, L. Pintelon, and G. Waeyenbergh, Criticality classification of spare parts: A case study, Int. J. Prod. Econ., vol. 140, no. 2, pp. 570-578, 2012.

[3] Van Horenbeek, A., Pintelon, L., Muchiri, P., Maintenance optimization models and criteria. International Journal of Systems Assurance Engineering and Management 1, 189–200., 2010.

[4] Al-Tarawneh, H.A., The main factors beyond decision making, Journal of Management Research, vol. 4, no. 1, 2012.

[5] Molenaers, A., Baets, H., Pintelon, L. and Waeyenbergh, G., Criticality classification of spare parts: A case study, International Journal of Production Economics, vol. 140, no. 2, pp. 570–578, 2012.

[6] Flores, B. E. & Whybark, D. C., Implementing multiple criteria ABC analysis. Journal of Operations Management, 7(1), 79–85. Elsevier, 1987.

[7] Bacchetti, A. and Saccani, N., Spare parts classification and demand forecasting for stock control: Investigating the gap between research and practice. Omega, vol. 40, no. 6, pp. 722–737, 2012.

[8] Naylor, J., Naim, M. and Berry, D., “Leagility: integrating the lean and agile manufacturing paradigms in the total supply chain”, International Journal of Production Economics, Vol. 62 No. 1, pp. 107-118, 1999

[9] Huiskonen, J., Maintenance spare parts logistics: Special characteristics and

strategic choices. International journal of production economics, 71(1), 125– 133. Elsevier, 2001.

[10] Partovi, F.Y. and Burton, J., “Using the analytic hierarchy process for ABC analysis”, International Journal of Operations & Production Management, Vol. 13 No. 9, pp. 29-44, 1993.

[11] Saaty, TL., Multi criteria decision making: the analytic hierarchy process, Revised and published by the author, Original version published by McGraw-Hill, NewYork, 1980.

[12] Gajpal PP, Ganesh LS, Rajendran C., Criticality analysis of spare parts using the analytic hierarchy process, International Journal of Production Economics, 1994.

[13] Gajpal, P.P., et al., Criticality analysis of spare parts using the analytic hierarchy process. International Journal of Production Economics 35 (1-3):293–297., 1994.

[14] Sharaf, M.A., Helmy, H.A., A classification model for inventory management of spare parts. Proceedings of seventh International Conference on Production, Industrial Engineering, Design and Control (PEDAC 2001), Alexandria, Egypt, 2001.

APPENDIX A: FEEDBACKS:

Feedback 1:

With respect to Primary Criteria, Using the scale from 1 to 9 (where 9 is extremely and 1 is equally important), please indicate (X) the relative importance of options A (left column) to options B (right column).																		
A Options	Extremely Important 9	8	Very Strongly Important 7	6	Strongly Important 5	4	Moderately Important 3	2	Equally Important 1	2	Moderately Important 3	4	Strongly Important 5	6	Very Strongly Important 7	8	Extremely Important 9	B Options
Machine Impact		X																Part Cost
Machine Impact			X															Demand Frequency
Machine Impact						X												Lead Time
Part Cost					X													Demand Frequency
Part Cost							X											Lead Time
Demand Frequency									X									Lead Time

With respect to Machine Impact, Using the scale from 1 to 9 (where 9 is extremely and 1 is equally important), please indicate (X) the relative importance of options A (left column) to options B (right column).																		
A Options	Extremely Important 9	8	Very Strongly Important 7	6	Strongly Important 5	4	Moderately Important 3	2	Equally Important 1	2	Moderately Important 3	4	Strongly Important 5	6	Very Strongly Important 7	8	Extremely Important 9	B Options
Stops Machine	X																	Not Stops Machine

With respect to Part Cost, Using the scale from 1 to 9 (where 9 is extremely and 1 is equally important), please indicate (X) the relative importance of options A (left column) to options B (right column).																		
A Options	Extremely Important 9	8	Very Strongly Important 7	6	Strongly Important 5	4	Moderately Important 3	2	Equally Important 1	2	Moderately Important 3	4	Strongly Important 5	6	Very Strongly Important 7	8	Extremely Important 9	B Options
More than $5000/unit			X															$500-$5000/unit
>$5000/unit	X																	<$50/unit
$500-$5000/unit			X															<$50/unit

With respect to Demand Frequency, Using the scale from 1 to 9 (where 9 is extremely and 1 is equally important), please indicate (X) the relative importance of options A (left column) to options B (right column).																		
A Options	Extremely Important 9	8	Very Strongly Important 7	6	Strongly Important 5	4	Moderately Important 3	2	Equally Important 1	2	Moderately Important 3	4	Strongly Important 5	6	Very Strongly Important 7	8	Extremely Important 9	B Options
+1 per year			X															<1 per year
+1 per year	X																	no-order last 3 year
<1 per year					X													no-order last 3 year

With respect to Lead Time, Using the scale from 1 to 9 (where 9 is extremely and 1 is equally important), please indicate (X) the relative importance of options A (left column) to options B (right column).																		
A Options	Extremely Important 9	8	Very Strongly Important 7	6	Strongly Important 5	4	Moderately Important 3	2	Equally Important 1	2	Moderately Important 3	4	Strongly Important 5	6	Very Strongly Important 7	8	Extremely Important 9	B Options
>60 days			X															31-60 days
>60 days	X																	<30 days
31-60 days					X													<30 days

Feedback 4:

With respect to Primary Criteria, Using the scale from 1 to 9 (where 9 is extremely and 1 is equally important), please indicate (X) the relative importance of options A (left column) to options B (right column).																		
A Options	Extremely Important		Very Strongly Important		Strongly Important		Moderately Important		Equally Important		Moderately Important		Strongly Important		Very Strongly Important		Extremely Important	B Options
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Machine Impact																		Part Cost
Machine Impact																		Demand Frequency
Machine Impact																		Lead Time
Part Cost																		Demand Frequency
Part Cost																		Lead Time
Demand Frequency																		Lead Time

With respect to Machine Impact, Using the scale from 1 to 9 (where 9 is extremely and 1 is equally important), please indicate (X) the relative importance of options A (left column) to options B (right column).																		
A Options	Extremely Important		Very Strongly Important		Strongly Important		Moderately Important		Equally Important		Moderately Important		Strongly Important		Very Strongly Important		Extremely Important	B Options
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Stops Machine																		Not Stops Machine

With respect to Part Cost, Using the scale from 1 to 9 (where 9 is extremely and 1 is equally important), please indicate (X) the relative importance of options A (left column) to options B (right column).																		
A Options	Extremely Important		Very Strongly Important		Strongly Important		Moderately Important		Equally Important		Moderately Important		Strongly Important		Very Strongly Important		Extremely Important	B Options
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
More than $5000/unit																		$500-$5000/unit
>$5000/unit																		<$50/unit
$500-$5000/unit																		<$50/unit

With respect to Demand Frequency, Using the scale from 1 to 9 (where 9 is extremely and 1 is equally important), please indicate (X) the relative importance of options A (left column) to options B (right column).																		
A Options	Extremely Important		Very Strongly Important		Strongly Important		Moderately Important		Equally Important		Moderately Important		Strongly Important		Very Strongly Important		Extremely Important	B Options
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
>1 per year																		<1 per year
>1 per year																		no order last 3 year
<1 per year																		no order last 3 year

With respect to Lead Time, Using the scale from 1 to 9 (where 9 is extremely and 1 is equally important), please indicate (X) the relative importance of options A (left column) to options B (right column).																		
A Options	Extremely Important		Very Strongly Important		Strongly Important		Moderately Important		Equally Important		Moderately Important		Strongly Important		Very Strongly Important		Extremely Important	B Options
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
>60 days																		31-60 days
>60 days																		<30 days
31-60 days																		<30 days

APPENDIX B: PRIMARY CRITERIA FEEDBACK ANALYSIS

Feedback 1:

Priorities

	Category	Priority	Rank
1	Machine Impact	59.2%	1
2	Part Cost	5.8%	4
3	Demand Frequency	16.3%	3
4	Lead Time	18.6%	2

Decision Matrix

	1	2	3	4
1	1	6.00	6.00	3.00
2	0.17	1	0.25	0.25
3	0.17	4.00	1	1.00
4	0.33	4.00	1.00	1

Number of comparisons = 6 **Consistency Ratio CR** = 6.8%

Feedback 2:

Priorities

	Category	Priority	Rank
1	Machine Impact	65.4%	1
2	Part Cost	10.7%	3
3	Demand Frequency	9.2%	4
4	Lead Time	14.7%	2

Decision Matrix

	1	2	3	4
1	1	8.00	7.00	4.00
2	0.12	1	2.00	0.50
3	0.14	0.50	1	1.00
4	0.25	2.00	1.00	1

Number of comparisons = 6 **Consistency Ratio CR** = 6.9%