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PRODUCT DISASSEMBLABILITY AND REMANUFACTURABILITY ASSESSMENT: A QUANTITATIVE APPROACH

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PRODUCT DISASSEMBLABILITY AND REMANUFACTURABILITY ASSESSMENT: A QUANTITATIVE APPROACH

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Mechanical Engineering in the
College of Engineering at the University of Kentucky

By

Ammar Ali

Lexington, Kentucky

Director: Dr. Fazleena Badurdeen, Associate Professor
Department of Mechanical Engineering
University of Kentucky, Lexington, Kentucky

2017

Abstract of Thesis

PRODUCT DISASSEMBLABILITY AND REMANUFACTURABILITY ASSESSMENT: A QUANTITATIVE APPROACH

Majority of the products get discarded at end-of-life (EoL), causing environmental pollution, and resulting in a complete loss of all materials and embodied energy. Adopting a closed-loop material flow approach can aid preventing such losses and enable EoL value recovery from these products. Design and engineering decisions made and how products are used impact the capability to implement EOL strategies such as disassembly and remanufacturing. Some underlying factors affecting the capability to implement these EOL strategies have been discussed in previous studies. However, relevant metrics and attributes are not well defined and comprehensive methods to quantitatively evaluate them are lacking. This study will first identify key lifecycle oriented metrics affecting disassemblability and remanufacturability. Then a methodology is proposed for the quantitative evaluation of these strategies considering the quality of returns, product-design characteristics and process technology requirements. Finally, an industrial case study is presented to demonstrate the application of the proposed method.

KEYWORDS: End-of-life ‘ilities’, Closed-loop material flow, Remanufacturing, Disassembly, Total Lifecycle Approach, Remanufacturability

MULTIMEDIA ELEMENTS USED: JPEG (.jpg)

Ammar Ali
Student’s Signature

10/12/17
Date

PRODUCT DISASSEMBLABILITY AND REMANUFACTURABILITY ASSESSMENT: A QUANTITATIVE APPROACH

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To my family

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Chapter 1 Introduction

1.1 Background

Over the years, environmental concerns have garnered more attention on the global manufacturing platform. This is due to stricter regulations, depleting availability of landfill spaces and the alarming rate of resource utilization. To address these concerns, manufacturing industry is attempting to evolve by embracing more sustainable ways of manufacturing (Zhang et al. 2013). Such efforts have caused the expansion of traditional manufacturing concepts to include the total lifecycle consideration of the manufactured products. Total lifecycle of a product is further divided into premanufacturing (PM), manufacturing (M), use (U), and post-use (PU) stages (Zhang et al., 2013). Resource extraction and raw material production constitute the 'PM' stage of a product. 'M' stage of the product involves components manufacturing, assembling, testing, packaging and distribution. 'U' stage comprises of product use by the customer. 'PU' is the last stage of the lifecycle where, the customer ceases using the product due to its end-of-use or end-of-life (EoL) (Zhang et al., 2013). Developments in 'PU' have been necessary to enable compliance with various take-back legislations, which have been developed to encourage the manufacturers to "close the loop" in the product lifecyle. New legislation forces companies to evaluate technical and economic implications of several possible alternatives to disposal, including disassembly, reuse, remanufacturing, and recycling (Mangun & Thurston, 2002). The primary advantage of this closed-loop approach is, a reduction in both the environmental impact of a product's lifecycle and the cost of compliance with product take-back laws (Mangun & Thurston, 2002).

1.1.1 *Total Lifecycle Approach and 6R-Methodology*

The total lifecycle approach implies that every step involved in the progression of a product's lifecycle from cradle to grave, has its impact on the economy, environment and the society (UNEP, 2017). These 3 aspects together, otherwise known as the triple bottom line (TBL), form the basis for developing the 6R-methodology to enable closed-loop material flow. Based on the work developed by the Institute for Sustainable Manufacturing (ISM) at the University of Kentucky, 6R methodology involves reduce, reuse, recover, redesign, remanufacture, and recycle to incorporate multiple lifecycles of a product and a closed-loop material flow, as shown in Figure 1 (Zhang et al., 2013).

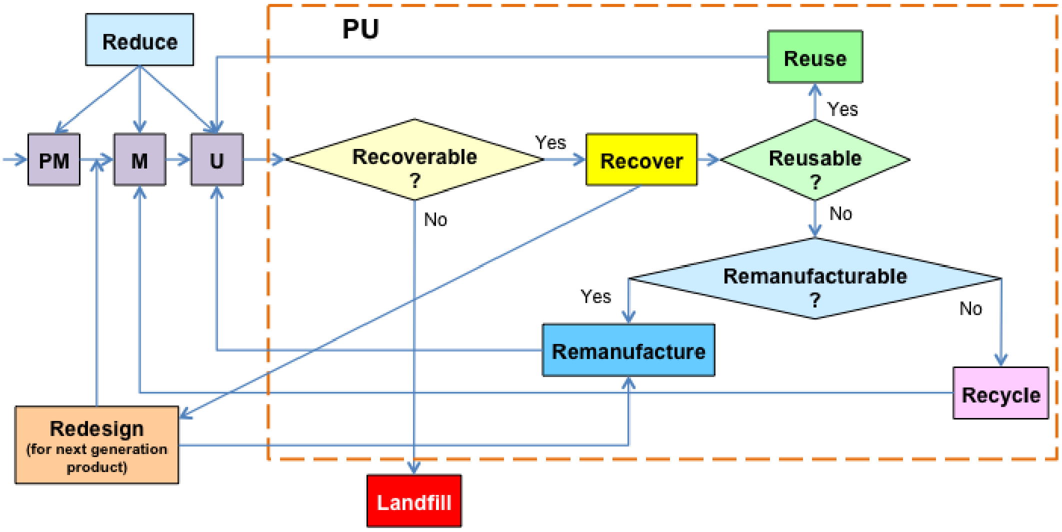


Figure 1 6R Methodology (Zhang et al., 2013)

Traditional 3R concept (Reduce, Reuse and Recycle) has often been considered as the basis of green manufacturing (Lu, 2015). The extended activities that convert 3R concept (EPA, 2017) into 6R methodology are Recover, Redesign and Remanufacture (Lu, 2015). In the following paragraphs, each 6R activity is described to better assist the Figure 1 in explanation of the 6R decision flow.

Recover is a series of activities that enables retention of embedded value of products/components/materials, energy, other resources, and information throughout the lifecycle for use in either the original or other applications (ISM, 2017).

Reuse is a series of activities to utilize products/sub-assemblies/components/waste without additional processing in a way that provides the required functionality in the original or other applications (ISM, 2017).

Remanufacture is a series of activities that seeks to restore products or components to satisfy or exceed the intended functionality and appearance (ISM, 2017).

Recycle is a process of converting products, components and/or residues into material(s) for either the original or other applications (ISM, 2017).

Reduce seeks to minimize the use of resources and waste generated throughout the lifecycle, at product, process and systems levels (ISM, 2017).

Redesign is the principle that seeks to modify or upgrade the product's engineering specifications by utilizing resources from earlier generation end-of-life products, considering changing customer requirements and technological advancements to improve the overall sustainability (ISM, 2017).

Due to the growing focus towards the closed-loop material flow, the application of product recovery, reuse, remanufacturing, and recycling strategies after product use has become more widespread (Aydin et al. 2017). Also, Public awareness and increased legislation are placing pressure on the development of effective take back and recycling of manufactured products at end-of-life (Sodhi & Knight, 1998). The reluctance of communities to open new waste sinks underscores the importance of developing methods and models for the management of end-of-life products (Sodhi & Reimer, 2001). This requires the establishing of suitable analysis tools, to evaluate the ease of disassembly and remanufacturing across the end-of-life practices (Reimer et al., 2000).

1.1.2 *End-of-life 'ilities'*

The term 'ility' has a Latin and French origination meaning 'ability' (Dictionary.com, 2016). In the context of the total lifecycle of a product, 'ility' is used as the prefix with various product, process and system related activities, features and key performance indicators (KPI). Hence, it is defined as the ability or capability to achieve a process, feature or a KPI. Few examples are reliability, availability, serviceability, usability, etc. In the context of EoL activities, few relevant 'ilities' are recoverability, reusability, remanufacturability, disassemblability, etc. (Aydin et al., 2017). Implementing EoL strategies (*i.e.* product recovery, reuse, remanufacturing) to facilitate the closed-loop material flow can help companies reduce environmental impact, improve regulation compliance, and reduce the cost of manufacturing and disposal, thereby increasing the global manufacturing competitiveness (Aydin et al., 2017).

Conceptual issues regarding several EoL 'ilities' have been investigated by previous studies (Aydin et al., 2017). Some of the recent ongoing research efforts for the same are being supported by the Digital Manufacturing and Design Innovation Institute (DMDII). They have had several calls for proposals centered around the usage of digital thread in system design to capture the "ility" tradeoffs (Terpenny, 2015). Even though the benefits of EoL strategies are known, the effectiveness of their implementation varies from product to product and from one industry to another. Such variation is due to the difference in the ability of accomplishing these EoL strategies.

1.2 Problem Statement

Growing awareness towards the benefits of the total lifecycle approach has led the global manufacturing platform to acknowledge the closed-loop material flow by embracing EoL strategies.

Disassembly and remanufacturing of returned products are such two widely implemented EoL strategies. But the factors affecting the disassemblability and remanufacturability have not been clearly identified. The previous literature investigates and presents various ways to quantify the benefits of these two ‘ilities’. But none have explicitly addressed the issue of quantitative assessment using these factors. To develop a better understanding, the factors affecting disassemblability and remanufacturability must be recognized. Next, a method needs to be developed based on these factors to explicitly quantify these two ‘ilities’.

1.3 Research Objectives

The scope of this research is to investigate disassemblability and remanufacturability. The goal here is to identify the factors, and determine the metrics that will enable the quantification of these ‘ilities’. Identification of factors/characteristics is the preliminary step in establishing the list of the measurable metrics for remanufacturability and disassemblability. Based on the problem statement, the work in this research is divided in to 2 research objectives:

- What are the key factors affecting the disassemblability and remanufacturability?
- How can these two 'Ilities' be quantitatively assessed based explicitly on the above factors?

1.4 Organization

The research work ahead is divided into seven Chapters. Figure 2 presents an overview of the structure of thesis. The literature review conducted to understand all the existing previous work is discussed in Chapter 2. Next chapters 3 and 4 document the quantitative methods developed for disassemblability and remanufacturability respectively. Chapters 5 and 6 present the data collection for, and application of, this methodology to an industrial case study. Chapter 7 summarizes the results obtained and presents a discussion about the developed methodology and its application. Lastly, Chapter 8 summarizes this research work and presents the scope of probable future work.

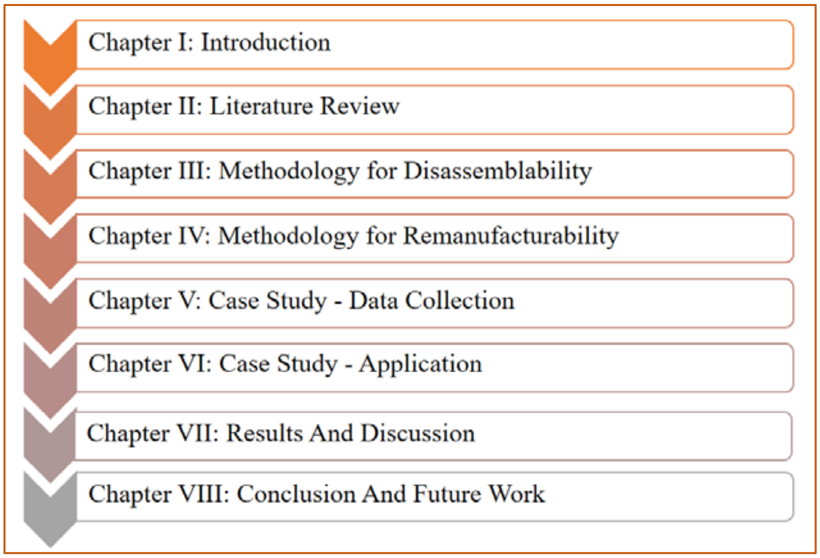


Figure 2 Thesis Organization

Chapter 2 Literature Review

Remanufacturing involves disassembling, cleaning, inspecting collected used products, and replacing some components because of physical condition or technology change, and reassembling and testing the final product (Aydin et al., 2017). The fact that disassembly is one of the sub-stages of remanufacturing, is a strong indication that the factors affecting ability to disassemble a product will also affect the ability to remanufacture the same. As per literature review, a general scheme for remanufacturing of a product is show in the Figure 3.

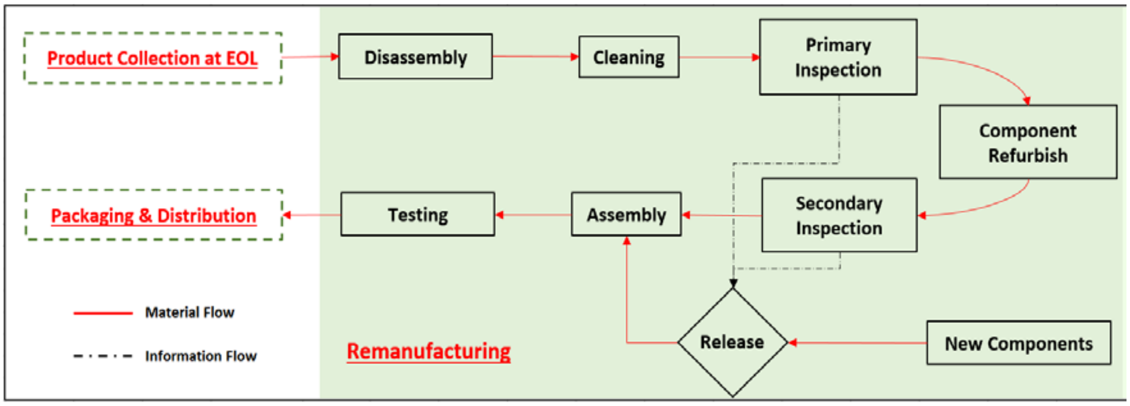


Figure 3 General Remanufacturing Scheme.

The above scheme assumes that there is no inspection prior to cleaning. Some of the returned components are replaced with new or used parts because of the OEM guidelines or failure to pass the primary and/or secondary inspection stages. The intent of this schematic is to understand the general layout of remanufacturing process and its sub-stages considered in the previous literature.

The result of a remanufacturing process is generally a product that has a like-new condition and can used by the customer for 2nd or more subsequent lifecycles. Previous studies have identified various factors and characteristics that affect the ability to implement the remanufacturing strategy. Priyono et al. (2016) proposed guidelines for design-for-remanufacturing (DFR) in terms of design characteristics, material content and assembly methods to enhance product remanufacturability and reduce environmental impact. Several qualitative characteristics for assessing the remanufacturability of an automobile door has been presented by Amezquita et al. (1995). These efforts were further extended by Bras and Hammond (1996) when they established a weighting-based quantitative methodology to assess the remanufacturability index of products based on design-for-assembly approach. Fang et al. (2016) and Soh et al. (2015) proposed metrics based on information entropy measure. These metrics were used to quantify the remanufacturability of the product design. A comprehensive scheme to score the process related handling effort during disassembly was presented by Desai and Mital (2003). Other work from Aras et al. (2004) presented an approach that quantifies remanufacturability by considering the quality of returned products. Similarly, the work of Ferguson (2009) and Bhattacharya and Kaur (2015) conducted categorization of the returned products and then graded them based on their quality characteristics. Based on the focus of investigation, in this study, the literature review for disassemblability and remanufacturability has been classified into five groups:

1. Product Design based
2. Process Technology related
3. Demand or Market focused
4. Incoming Quality related
5. Remaining life based

Previous work that identified factors and metrics based on the total part count, fastening methods, degree of accessibility of components, disassembly sequence, etc., have been classified under the product design based approach. Whereas, if the research focused on the factors such as time of assembly or disassembly, product handling effort, cleaning activities needed, ease of inspection and testing, etc., then they were differentiated as process technology based approaches. This is because the factors considered in this case affect the process related aspects of remanufacturing. Another aspect which has been frequently considered is that of the market conditions and customer demand. Several studies falling under this category consider that the factors like market price, return rate, demand rate, warranty cost, transportation cost, transportation permits, etc., effect the remanufacturability and disassemblability of a product. Simultaneously, some studies were also found that focus upon quality of the returned products. They consider that factors related with the quality of these products can aid in quantifying the two ‘ilities’. A relatively small portion of investigations for the two ‘ilities’ were found to have been based upon the remaining life of the returned products. Factors generally considered by them were, remaining life of the component, reliability of component, operation hours, etc.

While classifying the wide literature base, it was found that the approach of previous studies was not limited to just one aspect. Few adapted a single, but many considered two or more aspects as the focus of their approach. The above classification of literature work is presented in Table 1. This table also identifies if the listed studies are quantitative (Q) or qualitative (Ql) in nature. Out of the 35 relevant studies listed in Table 1, approximately half are based, specifically on the product design and the process related aspects. This signifies that majority of the previous literature focuses heavily upon the product and process related factors. The other combination of aspects considered, are that of; (1) process and demand, (2) process and remaining life, (3) process, demand, incoming quality, and remaining life (Kwak & Kim, 2010), etc. But, none of them collectively consider the product, process and incoming quality aspect under one study. This is a method related research gap identified in the previous studies. Previous literature, also lacked explicit metrics that could quantify the effect of incoming quality on the product's disassemblability and remanufacturability. This was identified as another gap but at the aspect level. Since, such a unique set of aspects was not considered before, identifying relevant factors and reasonable metrics for quantification and consolidation presented the next challenge.

The work proposed by Kwak & Kim (2010) is highly mathematical, hence, only users of specialized academic background can implement it. It was also observed that the other studies considering demand and remaining life, relied excessively on data collection. Assessment schemes that take longer to implement due to vast data requirement can be counter-productive for the crew and the organization. Furthermore, an outsourced process or a sub-process to a 3rd party vendor can make data collection cumbersome, due to issues of intellectual property rights. Of the studies that proposed quantitative methods, some (Bras & Hammond, 1996) (Wang et al. 2012) (Soh, Ong, Nee, & Soh, 2015) attempted to consolidate the results of the underlying metrics into a single score. The purpose here was to reflect the changes occurring across all the metrics or sub-metrics level through an overall integrated score. Such consolidation is helpful in conveying information to the user in a concise manner. Based on the above discussions, the proposed methodology in this research has certain objectives in terms of its desired strengths:

- Objective A: Methodology should add value to the previous work by considering combination of aspects that have not been considered before.
- Objective B: It should be easy to implement for any user, particularly in industry. Use of simple mathematical or empirical metrics is encouraged.
- Objective C: Data should be easily accessible and interdepartmental or interorganizational flow of information should be avoided, if possible.
- Objective D: Methodology should deliver scores on a scale which is easy to interpret. It should aggregate the results of the underlying metrics into a single score such that it further aids the ease of interpretation.

For this research, an approach is adapted that focuses upon the three aspects of product design, process technology, and the incoming quality of returns. This is because such an approach has not been considered in the previous studies (Refer Table 1). As observed from the literature review, the aspects of remaining life and market demand are assessed through metrics that have extensive interdepartmental or interorganizational data requirement. Thus, information collection in the case of these two aspects can become very challenging based on whether the information is accessible or not. Whereas, data gathering for a method based on the other three categories is easier because the returned product, and the process for remanufacturing (and disassembly) can generally be found in one department/organization. This is because they are not as widely spread across the supply chain as that of remaining life and market demand aspects.

2.1 Disassemblability

In this research, disassemblability is defined as the ability of disassembling a product. The expected result at the end of disassembly are all the disassembled components awaiting further activities.

2.1.1 *Factors affecting disassemblability*

Fang et al. (2016) proposed an integrated approach for product remanufacturing assessment and planning. In this they have identified various factors and characteristics like complexity of disassembly, fastener accessibility, disassemblability, recoverability (via disassembly), and optimal disassembly sequence that effect the ability to disassemble the product. Another similar work by Soh et al. (2015) has enlisted factors for complexity Index, accessibility index, F-measure and Z-score that assess the product disassemblability based on fastener count, angle of approach, component accessibility and optimal disassembly sequence, respectively.

Desai and Mital (2003) have proposed a disassemblability evaluation scheme which scores the product's disassembly process based on effort required for: handling the core, positioning the tool, and exerting the force while pushing, pulling, twisting and turning activities. Another work by Gungor and Gupta (1999) focused on the types of fastening methods by evaluating the connection types based on factors like complexity of disassembly motion, tool complexity, and disassembly time. Fujimoto et al. (2001) adopted an approach for assessing the ability to disassemble a product based on the factors like degree-of-freedom (DoF) of components, directionality of picking, directionality of accessibility and directionality in support.

Table 1 Classification of literature work

Relevant Literature	***Quantitative (Q) / Qualitative (L)***	**Approach Focus**				
		Product Design	*Process Technology*	*Demand or Market*	*Incoming Quality*	*Remaining life*
Fang, et al. (2015)	Q	•				
Armacost et al. (2005)	L		•			
Zhang et al. (2013)	Q					•
Mangun & Thurston (2002)	Q		•			•
Kaebernick et al. (2003)	Q			•		•
Kaebernick and Anityasari (2008)	Q		•			•
Robotis et al. (2012)	Q		•			•
B. Lu et al. (2014)	Q		•	•		
Amezquita et al. (1995)	L	•	•			
Ijomah et al. (2007)	L	•	•	•		
Bras & Hammond (1996)	Q	•	•			
Sundin & Bras (2005)	L	•	•			
Shu & Flowers (1999)	Q		•			•
Lebreton & Tuma (2006)	Q		•	•		
Bao et al. (2006)	Q		•	•		•
Yao et al. (2014)	Q	•	•			
Feng et al. (2013)	Q	•	•			•
Polotski et al. (2015)	Q		•	•		
Johnson & Wang (1998)	Q	•	•			
Kim & Goyal (2011)	Q		•	•		
Kwak & Kim (2010)	Q		•	•	•	•
Umeda et al. (2013)	Q	•	•			
Soh et al. (2015)	Q	•	•			
Desai & Mital (2003)	L	•	•			
Tian et al. (2013)	Q		•			
Gungor & Gupta (1999)	Q	•	•			
Fujimoto et al. (2001)	Q	•				
Kroll & Carver (1999)	Q	•	•			
Gadh et al. (1998)	Q	•	•			
Suga et al. (1996)	Q	•				
Aras et al. (2004)	Q			•	•	
Giudice & Kassem (2009)	Q	•	•			
Wang, et al. (2012)	Q		•			
Mabee et al. (1999)	L	•	•			
Das & Naik (2002)	Q	•	•			
Bhattacharya & Kaur (2015)	Q		•		•	

Tian et al. (2013) proposed an optimization method using genetic algorithm to determine the optimal disassembly route for the product. This work suggested that the cornerstone of improving the disassemblability is by determining the best disassembly sequence based on the optimal combination of disassembly time and disassembly cost. Giudice and Kassem (2009) considered similar factors that assess the disassemblability by analyzing and redistributing the disassembly depth. In this method, the disassembly depths of product components were established in relation to their need for removal and recovery at end-of-life. Another literature effort that was built upon disassembly time estimation and disassembly design efficiency is that of Kroll and Carver (1999). This work was focused on the mechanical design aspect of the products, and developed a design-for-disassembly (DFD) evaluation metrics. It was proposed that this metrics be used when designing new products to make their disassembly for recycling easier.

Johnson and Wang (1998) proposed a similar method that considers factors like disassembly cost, disassembly time, and reclamation value for disassemblability. They defined disassemblability as the ability to optimize the design and disassembly process for removal of specific parts or materials in a manner which will simultaneously minimize costs and maximize the material value to be reclaimed. Bhattacharya and Kaur (2015) proposed an optimization approach to maximize recovery value of the returned product based on whether the disassembled components were acceptable or not, number of refurbished components and demand. Gadh et al. (1998) created a virtual disassembly software tool which would assess the design efficiency of a product for its disassembly based on the factors like: ease of product disassembly, disassembly sequencing and disassembly cost. Other factors considered by the same group were number of components, accessibility, and material of components. One of the earliest work on disassemblability was by Suga, et al. (1996). They proposed a quantitative disassembly evaluation which considered energy for disassembly, and entropy for disassembly as the key factors.

The complete list of factors identified from the previous literature effecting remanufacturability and disassemblability has been compiled and presented in Appendix C. Given the similarities and differences in the focus of the previous studies (refer Table 1), several factors were considered in multiple works, whereas few were unique. To succinctly identify the least number of factors that could effectively reflect the initial compiled list without repetition but still considering the unique factors, Appendix C was further shortlisted to create one list for remanufacturability and another for disassemblability. Another basis for shortlisting the factor was the expert opinion received from prospective case study partner, SRC of Lexington. This was done to keep the factors more realistic to the case study itself. The factors identified for disassemblability are shown in the Table 2.

2.1.2 *Metrics for Disassemblability*

The list of factors identified in the Table 2 will drive the selection or development of metrics that will be used for the assessment of different aspects of disassemblability. Like the identified factors, metrics relevant for disassemblability assessment presented in the previous studies have been discussed under the categories based on product design, process technology and incoming quality of returned products.

Product Design based metrics

Fang et al. (2015) proposed a metric which assesses the product complexity based on, the number of fasteners for each type and total number of fastener types. Fastener type in this context refers to different variety of fasteners like, snap fit, interference fit, welded fit, screwing fit etc. The proposed metric in this case suggested that the product becomes more complex with increase in types of fasteners and with increase in the count of fasteners for each type. But, this approach did not consider the variation in the difficulty behind different types of fasteners. Das and Naik (2002) proposed an unfastening effort rating (U-rating) based scheme. This scheme assigned different U-ratings based on the kind of fastener type used. An explicit metric that considers the number of fastener types, number of fasteners for each type and the unfastening effort involved for different types of fasteners was not found. Soh et al. (2015) proposed a metric to assess the accessibility of a component. This approach is based on the information entropy approach which uses information available from measurement of the exposed dimensions available due to product design.

Process Technology based metrics

Bras and Hammond (1996) proposed a metric based on the design for assembly analysis (DFA) which compares ideal time for disassembly with the actual time taken to disassemble. The ideal disassembly time was established based on DFA principles. The metrics scores the actual disassembly time on a scale of 0 to 1. Desai and Mital (2003) presented a comprehensive scheme for scoring the handling effort required during the disassembly process. This scheme rates the aspects of, Material handling for its weight and size, force exertion while unfastening or uncoupling components, tool positioning for symmetric and asymmetric cores, angle of approach required for unfastening, and type of tooling required.

Table 2 Factors Identified for Disassemblability

Factors \ Literature	Fang et al. (2015)	Soh et al. (2015)	(Tian et al., 2013)	(Giudice & Kassem, 2009)	(Gungor & Gupta, 1999)	(Desai & Mital, 2003)	(Fujimoto et al., 2001)	(Kroll & Carver, 1999)	(Johnson & Wang, 1998)	(Gadh et al., 1998)	(Suga et al., 1996)	(Bhattacharya & Kaur, 2015)	Armacost et al. (2002)	Bras & Hammond (1996)	Das & Naik (2002)
Number of Fastener types	X				X					X					
Number of Each type of fasteners	X	X			X			X		X					
Difficulty of Each Fastener Type	X	X						X							
Number of total components			X	X	X			X	X					X	
Disassembly Time						X					X			X	
Disassembly Effort				X	X				X	X					
Labor Cost				X	X				X	X				X	
Setup and Tool Cost												X		X	
Quality of Returns	X	X		X						X		X			
Dimensional Access of Components		X		X			X								
Degree of freedom of Components											X				X
Number of Inspected Components														X	
Total non-fastener count													X		
Cost of New Components													X	X	

Incoming quality of the returned product

Only few of the previous studies discuss this aspect. But apart from several grading schemes, no explicit metrics have been proposed that can capture the quality of the returned product.

2.2 Remanufacturability

In this research, remanufacturability is defined as the ability to remanufacture a product. As disassembly is one of the sub-processes of remanufacturing (Aydin et al., 2017), the list of factors and metrics that apply to disassemblability, also apply to remanufacturability. But remanufacturability goes beyond disassemblability to consider other extra factors and metrics which will be discussed further in section 2.2.1 and 2.2.2.

2.2.1 *Factors affecting remanufacturability*

Bras and Hammond (1996) proposed a weighting-based quantitative methodology that assessed the remanufacturability index of products based on the DFA approach. They considered factors such as, total number of components, time of disassembly, time of assembly, number of components refurbished, number of components replace, cost of cleaning, time of testing and number of components inspected. Sundin and Bras (2005) identify other factors like ease of access, ease of handling, and ease of separation to study how they affect the remanufacturability of a product.

Armacost et al. (2005) assessed the design for remanufacturability using quality function deployment (QFD). They defined remanufacturability as a characteristic of a product that represents the degree to which a product may be easily remanufactured. Similar work by Mabee et al. (1999) presented design charts for remanufacturing assessment which considered factors associated with disassembly, sorting, cleaning, refurbishment and reassembly. Shu and Flowers (1999) proposed a framework for the selection of product lifecycle fastening and joining methods.

They considered factors like remanufacture cost, recycling cost, new component cost, maintenance cost, etc. Earlier work by Amezquita et al. (1995) characterizes the remanufacturability of the engineering systems based on factors like ease of disassembly, ease of inspection, ease of cleaning, ease of reassembly; number of reusable components and types of fasteners and interfaces. Wide list of factors identified from the literature are shown in Appendix C. Like disassemblability, the more succinct shortlisted factors for remanufacturability are shown in Table 3.

2.2.2 *Metrics for Remanufacturability*

Product Design based metrics

Bras and Hammond (1996) proposed a metric that rates the process based on the number of inspected components. With this, they have attempted to capture the complexity brought in the remanufacturing of product due to frequent component inspections. The other relevant proposed metrics have already been discussed under disassemblability.

Process Technology based metrics and Quality of returned products

Bras and Hammond (1996) proposed several metrics under this category. They attempted to capture the effort invested behind cleaning, and testing activities during remanufacturing by scoring the current state of the process with an ideal benchmark. The other metrics they considered were based on rating the disassembly time, assembly time and the refurbishing process. The metrics for rating the disassembly and assembly time compared the actual time with a benchmark established on DFA principles. These metrics are scored on a scale of 0 to 1. The other relevant metrics have been already discussed under disassemblability. Incoming quality of returned product in case of remanufacturability is like disassemblability and has already been discussed under the section 2.1.2.

2.3 Combinatorial Metrics

Various combinatorial metrics were identified during the literature review. A quantitative combinatorial metric ‘F-measure’ was proposed by Soh et al. (2015) which integrates the scores of two metrics of choice to package them in to a single value. Usage of such a combinatorial metric as the part of the assessment methodology for the remanufacturability and disassemblability is proposed for this research. Details of how and why the F-measure is used, will be discussed in Chapter 3. Another combinatorial metric is presented by Bras and Hammond (1996). It is based on inverse weighted addition approach. The concept of adding inversely is not uncommon in harmonic series or in the design of simple electronic circuits. In order to identify the equivalent resistance of parallel resistors in an electronic circuit, the resistances are added inversely (Bras & Hammond, 1996). The application of this metric is proposed in combining the scores of sub-metrics which fall under the category of process technology. The weights in this case are derived using a priority matrix based on the relative investment behind each of the sub-processes (*i.e.* cleaning, inspection, disassembly, assembly, testing, etc.) of remanufacturing. The usage of this metric is further discussed in Chapter 3.

Table 3 Factors identified for remanufacturability

	(Fang et al., 2015)	(Soh et al., 2015)	(Tian et al., 2013)	(Giudice & Kassem, 2009)	(Gungor & Gupta, 1999)	(Desai & Mital, 2003)	(Fujimoto et al., 2001)	(Kroll & Carver, 1999)	(Johnson & Wang, 1998)	(Gadh et al., 1998)	(Suga et al., 1996)	(Aras et al., 2004)	(Wang, Zhang, & Chen, 2012)	(Armacost et al., 2002)	(Sundin & Bras, 2005)	(Bhattacharya & Kaur, 2015)	(Mabee et al., 1999)	(Shu & Flowers, 1999)	(Bras & Hammond, 1996)	(Amezquita et al., 1995)
Number of Fastener types	X				X					X										
Number of each type of fasteners	X	X			X			X		X										
Number of total components	X	X						X												X
Disassembly Time			X	X	X			X	X				X		X		X		X	X
Disassembly Effort						X					X				X					
Labor Cost				X	X				X	X			X			X		X	X	
Setup and Tool Cost				X	X				X	X			X			X		X	X	
Quality of Returns												X				X				
Dimensional Access of Components	X	X		X			X			X					X					
Degree of freedom of Components				X			X								X					
Number of Inspected Components																	X		X	
Total non-fastener count														X						
Assembly time															X				X	X
Cost of Cleaning Activities															X		X	X	X	
Testing Time																	X		X	
No. of Refurbished Components																			X	
Cost of New Component														X						

Chapter 3 Methodology for Disassemblability Assessment

This chapter proposes a methodology for disassemblability which is based on the factors identified in Table 2. The identification of these factors has been discussed briefly in the literature review. In the discussions ahead, reasoning behind the selection of various factors and related metrics is presented. Figure 4 provides an overview of the proposed methodology for disassemblability. This methodology has been broken down into four phases for the ease of understanding (See Figure 4). The first phase is the assessment of the product design. This phase attempts to capture the effect of product's design related features on its disassemblability. A majority of the earlier work attempts to asses this aspect either quantitatively or qualitatively, where, the former is more common. In this research, the basis of analysis presented for all the four phases is quantitative. The literature extensively identifies various design and non-design based factors that affect the disassemblability of product. However, the attention to non-design factors in literature is not as comprehensive. For this research, the product design related assessment is represented by Product Feature Index for Disassemblability (PD_D).

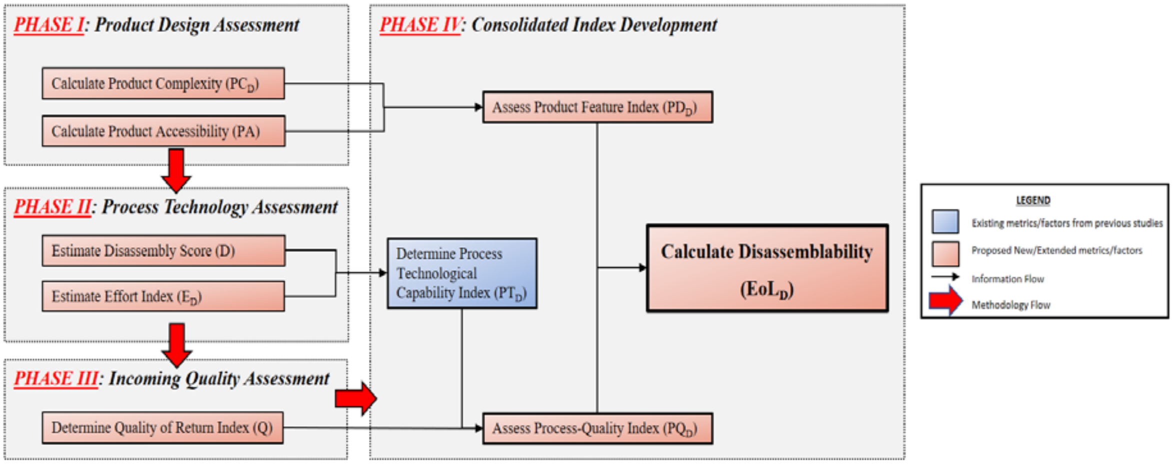


Figure 4 Methodology of Disassemblability Assessment

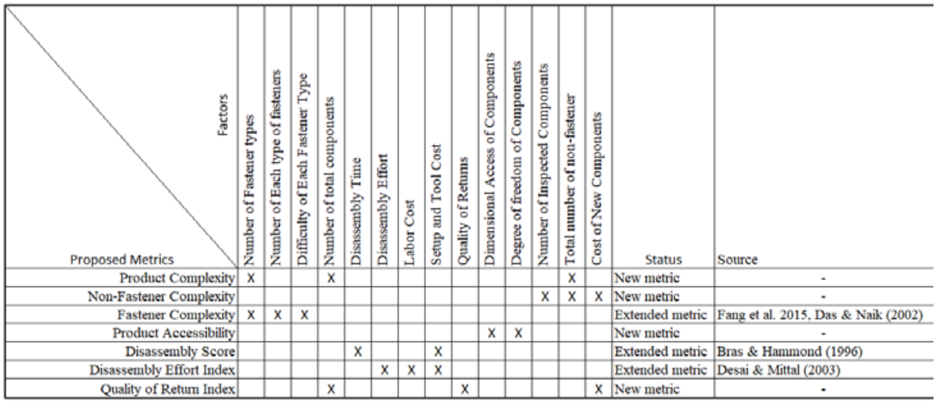
The next phase considers the assessment of process technological capability. Various studies acknowledge the effect of process related activities on disassemblability (Bras & Hammond, 1996 ; Armacost et al. 2005; Johnson & Wang, 1998) which has inspired this consideration. It is important to mention that most of literature primarily considers design based factors and that the non-design factors are not considered comprehensively. Another aspect that considers the non-design factors is that of the incoming quality of returns. This is assessed in the third phase of the methodology through a quality grading metrics. The basis of this aspect is the limitation that is imposed on the disassemblability of a product due to unacceptable quality of the EoL components. Lower or unacceptable quality of returns can make it impossible to successfully disassemble a product. Also, an outdated disassembly process (in terms of technology and practice) can have the same effect on the products disassemblability irrespective of the incoming quality.

For example, slower machines or higher core setup time can increase disassembly lead time, thereby, increasing the total disassembly cost. In cases where there is a small profit margin, this can make the process infeasible. Whether the incoming quality is acceptable is relevant at this point since the overall process depends on the disassembly being profitable. One solution is to either upgrade the process or lift the profit margin. Realistically, raising the profit margin is not possible in all the products since the market dynamics and customer needs are not dictated by the service providers except may be in the case of a very few products where the OEM has the market monopoly. The other reasonable solution would be to upgrade the line capability by economically feasible investments.

Another example would be of a disassembly process, where the technological capability is state-of-the art, but the incoming quality is beyond the point of reclamation by the EoL strategies. In such a scenario, the process capability is redundant as the incoming quality is far below the acceptable grade. Thus, it is reasonable to consider both process technological capability and quality of returns in the assessment of disassemblability. Process Technological Capability and Quality of Returns Index for disassemblability in this research are represented by ‘PT_D’ and ‘Q_D’ respectively.

3.1 Identification of Metrics

Capability to disassemble a product depends on various factors identified in Table 2, some more relevant than others. This table is a shortlisted based on the wide list of factors (relevant to disassembly) identified from the literature review (Refer Appendix C). A group of metrics is proposed that are explicitly based on these factors. The source of these metrics ranges from adaptation and/or extension of the previous studies, to the newly proposed metrics unique to this research work. Reasoning behind of each metric will be discussed along with their introduction in the upcoming sections. Further, an overview of the connection from the proposed group of metrics to the factors listed (See Table 2) is shown in Figure 5.



Factors Proposed Metrics	Number of Fastener types	Number of Each type of fasteners	Difficulty of Each Fastener Type	Number of total components	Disassembly Time	Disassembly Effort	Labor Cost	Setup and Tool Cost	Quality of Returns	Dimensional Access of Components	Degree of freedom of Components	Number of Inspected Components	Total number of non-fastener	Cost of New Components	Status	Source
Product Complexity	X			X									X		New metric	-
Non-Fastener Complexity												X	X	X	New metric	-
Fastener Complexity	X	X	X												Extended metric	Fang et al. 2015, Das & Naik (2002)
Product Accessibility										X	X				New metric	-
Disassembly Score					X			X							Extended metric	Bras & Hammond (1996)
Disassembly Effort Index						X	X	X							Extended metric	Desai & Mittal (2003)
Quality of Return Index				X					X					X	New metric	-

Figure 5 Metrics proposed to assess disassemblability assessment

Figure 5 shows what metrics are considered to evaluate relevant factors to evaluate disassemblability in the methodology proposed in this research. It also shows if the listed metrics are borrowed and extended, or if originally proposed in this research. It can be observed that several factors are considered in multiple metrics. This is not to be confused with considering a certain factor twice. Rather, multiple metrics utilize data collected from one or more factors. For the ease of understanding, the proposed metrics and the reasoning behind each metric is addressed from Phase I to Phase IV in the upcoming sections.

3.2 PHASE I: Product Design Assessment

'PD_D' represents the ease with which the product can be disassembled based on its design characteristics. 'PD_D' builds upon two sub-metrics known as; (1) Product Complexity for disassemblability (PC_D), and (2) Product Accessibility (PA), as shown in Figure 6.

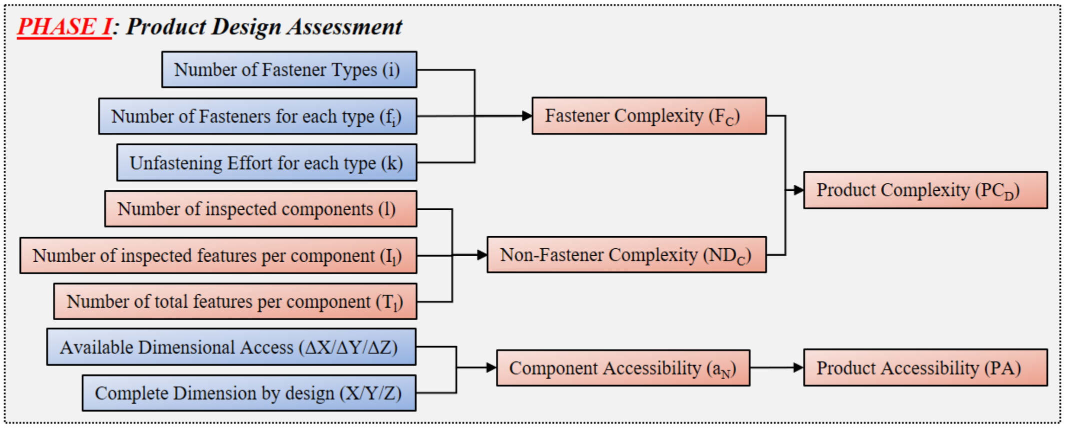


Figure 6 Methodology for Product Design Assessment

These sub-metrics are discussed further in sections 3.2.1 and 3.2.2 respectively. The metric for 'PD_D' itself is discussed in the section 3.5.1.

3.2.1 *Product Complexity for Disassemblability (PC_D)*

In this research work, 'PC_D' represents the ease with which the product can be disassembled based on the fastener and non-fastener complexity. The complexities that arise due to the unfastening of various fasteners during the product disassembly process is expressed under the metric 'Fastener Complexity (F_C)'. Whereas, the complexity brought about by quick inspections activities of critical non-fastener components is captured by the metric 'Non-Fastener Complexity during disassembly (ND_C)'.

Fastener Complexity (F_C)

The design of a product has a significant effect on the ease of disassembly. The importance of number of components, number of fasteners, different fastener types, tolerancing of critical components, etc., on the ability to disassemble a product have been highlighted in the literature (Fang et al., 2015) (Soh et al., 2015). Work by (Fang et al., 2015) specifically considers the number of fasteners to affect the complexity of the disassembly which is quantified by their proposed metric M_{com}, shown in Equation (1).

$$\boxed{M_{com} = \sum_{i=1}^{N_t} Log_2\left(N_f(i) + 1\right)} \tag{1}$$

where,

- N_t is the number of fastener types, and
- $N_f(i)$ is the number of fasteners of each type i.

Equation (1) is based on the information entropy measure defined as the average amount of information produced by a stochastic source of data (Gray, 2011). As per this metric, disassembly tends to be more complex with increasing number of fasteners, and the number of fasteners of each type. However, the approach proposed by Fang et al. (2015) does not consider the effect of having multiple fastener type other than merely accounting for their existence. Not all fastener types have the same level of difficulty while unfastening; some require more effort than the others. The limitation to the method proposed by Fang et al. (2015) is that it gives the same weightage to all the fastener types, assuming equal difficulty. In a separate work by Das & Naik, (2002) different fastener types are classified broadly into three groups based on the nature of the mating relationship:

- Type 1 mating: Parts are assembled with separate fasteners.

- Type 2 mating: Parts are assembled with fasteners integral to one of the parts.

- Type 3 mating: Parts are mating but there is no direct fastening involved.

In this research, to avoid confusion, type 1, 2, and 3, will be referred to as category 1, 2, and 3, respectively. Das & Naik, (2002) classify category 1 and 2 as Separate and Integral Fasteners respectively. They also present a list for each category of fastener (*i.e.* 1, and 2) which are shown in Table 4 and Table 5 respectively. These lists contain a sub-classification of generally used fasteners with their respective U-ratings (unfastening ratings).

Table 4 List of Category 1 (Separate) Fasteners (Das & Naik, 2002)

Code	Fastener Type	U-Rating
1	Nail with head	1.5
2	Nail w/o head or Pin	1.8
3	Screw/Bolt standard head	1.4
4	Screw/Bolt specialty head	2.2
5	Nut & Bolt	2.1
6	Rivets/Staples	2
7	Retaining Rings/Circlips	2.5
8	Tape	1.7
9	Adhesive	2.1
10	Welded	4
11	Velcro/Zipper	1
12	Releasable Clips	1.8

Table 5 List of Category 2 (Integral) Fasteners (Das & Naik, 2002)

Code	Fastener Type	U-Rating
13	Cylindrical Snap Fit	1.6
14	Cantilever Snap Fit	1.3
15	Seam/Crimp Joint	1.6
16	Interference Fit	1.8
17	Integrally Threaded Part	2.2
18	Socket and Plug	1.2

There is no such list for Category 3 fasteners (Refer Table 4 and Table 5) since, they involve two or more non-fasteners locking each other's motion in any of the Six degrees of freedom (6DoF) configuration. 6DoF refers to the freedom of movement of a rigid body in three-dimensional space (Paul, 1981). Thus, by description, there are no actual fasteners involved. Hence, they don't require any unfastening effort. Integral fasteners, on other hand are primarily non-fasteners which have a secondary function of inducing a fastening effect while in contact with the other fastener or non-fasteners. Lastly, category 1 fasteners, are the type of components which are having the primary function of inducing a fastening effect, when in contact with the other fasteners or non-fasteners. These are thus, also known as Separate Fasteners (Das & Naik, 2002). Hence, the total number of components (N) is equal to the sum of the number of non-fasteners (nf) and number of separate fasteners (f).

In this research, the work of Das and Naik (2002) is considered. Let the category indexing be represented by 'j' such that, when category is 1,2 or 3, 'j' is 1,2 or 0 respectively. Also, let the notations for the number of fastener types and the number of fastener for each type be 'i' and 'f_i' respectively. Now, an extension of Equation (1) is proposed, by integrating some additional factors to quantify the fastening effort. This is denoted by 'F_A' which is also known as the Actual Fastener Index. 'F_A' represents the actual fastening complexity of the current product design. Table 4 and Table 5 present the U-ratings for different fastener types. Let 'k' represent these U-ratings going forward. The modified expression for 'F_A' thus, is shown in Equation (2).

$$\boxed{F_A = \sum_{0}^{\mathrm{i}} j * k * \left(Log_2(\, f_i + 1)\right)} \qquad (2)$$

where,

F_A – Actual Fastener Index

j – Category index of fastener (where, j = 1, 2 or 0 for Category 1, 2 or 3 respectively)

k – U-rating for each fastener type obtained from Table 4 and Table 5 respectively.

The U-ratings listed in Table 4 and Table 5 are not completely unique for each fastener type. The work of Das and Naik (2002) clearly acknowledges that the ease of unfastening decreases in the order of Category 3 > Category 1 > Category 2. Hence, as a medium for differentiation, it is reasonable for 'j' to be introduced in the Equation (2). Such that, when Category is 1, 2 or 3, j is equal to '1', '2' or '0', respectively. Due to this, even with the similar U-ratings on the fastener level, the value of 'F_A' between product design with only category 1 fasteners will be lower compared to the one with only category 2 fasteners. And when, the product design contains only category 3 fasteners, then j = 0, which causes the value of 'F_A' to be equal to zero. This confirms to the logic of having only category 3 fasteners, in which case the fastening effort required is non-existent, thus leading 'F_A' to be zero. Three extreme cases of fastener configuration have been used to reason the inclusion of 'j', but for a more realistic product design, this is not a common occurrence since the fastening methods generally used exist in different categorical proportions.

Based on the literature review and the extensions proposed, Equation (2) does well to assess the current configuration of the product design in case of fastener complexity. Although, the goal of scoring the existing product design can only be achieved if the actual index is compared with a baseline or an ideal case. This is done so because intention of the proposed methodology is to generate a score between '0' and '1', so that the user can get an idea of how much the current design/process characteristic enables the disassemblability. All the sub-metrics discussed ahead follow a similar pattern where the current design or process characteristics are assessed and compared with a baseline or a scale to return a value between '0' and '1'. Here, '0' means the lowest and '1' implies the highest disassemblability for the respective aspect under consideration. Same applies to 'F_A'.

Thus, an expression is developed to compute the unfastening effort required if the simplest of all fasteners was used for the same product. This expression is referred to as the 'F_I' or the Ideal fastener index. Value of 'F_I' is unique for each product, as the simplest applicable U-rating (or 'k') depends on the simplest applicable category index 'j' which in turn is determined from the list of fasteners present in the bill of materials (BOM) of that product. One can argue that the best case is when all the fasteners fall under category 3. Thus, implying that category index 'j' is zero. But such a case is an exception and cannot be treated as a baseline because replacing all the fasteners with category '3' fasteners would require grave changes in the design which is not realistic. However, it is more reasonable to consider replacing integral fasteners with separate fasteners. Thus, the lowest applicable value for 'j' is 1 and not '0'. Following that, the respective minimum U-rating as per the Table 4 and Table 5 should be allotted. The proposed metric for F_I is given by Equation (3).

$$\boxed{F_I = \text{Min.}(\text{j}) * \text{Min.}(\text{k}) * \left(Log_2(\sum f_i + 1)\right)} \quad (3)$$

where,

f_i – Total number of fasteners

Min. (j) – Minimum applicable category index of fastener

Min. (k) – Minimum applicable U-rating given that the Min. (j) of fastener is known

It is proposed that the ratio of 'F_I' and 'F_A' be taken to generate a score for the current fastener complexity index. Let this be represented by 'F_C'. Hence, when 'F_A' increases, the resultant ratio lowers. And, when it decreases, the same ratio increases. This proposed trend is used to imply that the disassemblability improves when 'F_A' is closer to the 'F_I' and vice versa. The proposed metric for F_C shown in Equation (4).

$$\boxed{F_c = \frac{F_I}{F_A}} \tag{4}$$

Non-fastener Complexity during Disassembly (ND_C)

Disassembly process generally involves one or more quick inspection activities for some critical dimensions of certain critical non-fasteners. The investment related impacts behind inspection activities have been considered by the previous studies (Bras & Hammond, 1996). But the complexity introduced due to the inspection of critical dimensions have not been considered before. Therefore, operators are required to be more aware and possess better auditing skills. In this research, it is proposed that the impact of such inspections to both the 'ilities' be considered in two ways. One from the product design aspect, which is dependent on the number of features that should be measured. The other is from the process related aspect, which is dependent on the investment involved (Bras & Hammond, 1996). It is assumed in the case of disassemblability, that the requirement for elaborate inspection procedures is absent. Since, the inspection activities are generally very quick and limited towards dimensional measurements and condition observation. Thus, the process aspect of inspection is negligible only in the case of disassemblability. The design aspect however, may or may not involve inspection of certain dimensions for critical non-fasteners. Such non-fasteners are generally the costlier components in the BOM. Due to the assembled state of the non-fasteners, not all the critical features are available for inspection. Considering the features which are available, not all are always inspected. Thus, the factors like the number of inspected non-fasteners and the cost of new component play an important role in determining the disassemblability from the perspective of non-fastener complexity. Let's assume:

1. the number of inspected non-fasteners during disassembly be given by 'l'.
2. the total number of available features for inspection of l^{th} non-fastener during disassembly be given by 'T_l'.

3. the total no. of inspected features of l^{th} non-fastener during disassembly be given by 'I_l'.
4. the cost of the inspected l^{th} non-fastener be given by 'C_l'.
5. the cost based weight for the inspected of l^{th} non-fastener during disassembly be given by 'W_l'

Hence, the proposed metric for 'ND_C' is shown in Equation (5).

$$\boxed{ND_C = \left[\sum_{1}^{l}\left(1 - \left(\frac{I_l}{T_l}\right)\right) * W_l\right]} \tag{5}$$

where,

'W_l' is assessed by the proposed metric shown in Equation (6).

$$\boxed{W_l = \frac{C_l}{\sum C_l}} \tag{6}$$

To derive a complexity score for the complete product, a weighted addition for ND_C and F_C is proposed. By using the weights z_1 and z_2, skewing the overall complexity score towards either non-fasteners or fasteners is avoided. The proposed new metric for the Product Complexity for disassemblability (PC_D) is given by Equation (7).

$$\boxed{PC_D = (z_1 * ND_C) + (z_2 * F_C)} \tag{7}$$

where,

z_1 – weight for average non-fastener complexity

z_2 – weight for average fastener complexity

Equation (8) give the relation between the weights z_1 and z_2, respectively. Equation (8), (9) and (10) are established in such a way, that z_1 and z_2 indicate the proportion of non-fasteners and separate fasteners with respect to the total number of components, respectively.

$$\boxed{z_1 + z_2 = 1} \tag{8}$$

where, z_2 is given by the Equation (9).

$$\boxed{z_2 = \frac{f}{N}} \tag{9}$$

And, z_2 is given by the Equation (10).

$$\boxed{z_1 = \frac{nf}{N}} \tag{10}$$

where,

f – total no. separate or category 1 (*i.e.* j = 1) fasteners

nf – total no. of non-fasteners

N – total no. of components

It is important to mention that certain components generally have a dual function. For example, an oversized bushing is primarily a wearable non-fastener with a secondary function to support the interference fit. Such a component is counted as a non-fastener despite its integral fastening feature. Thus, when determining ‘f’, only those components are counted whose primary function is to be a fastener (*i.e.* nut, screw, etc.). Such components are also known as separate fasteners (or category 1). This way, the user can avoid double counting of components. Figure 5 earlier was presented to show the intended connection between the proposed metrics and the underlying identified factors in Table 2. Considering the discussions presented for each of the metrics proposed under the product complexity aspect, it is reasonable to conclude that information from all the intended factors have been used as suggested earlier in Figure 5.

3.2.2 *Product Accessibility (PA)*

Various literature (Soh et al., 2015) (Suh, 1990) considers the accessibility, or not, of the components to have a significant impact on the disassemblability of the product. Accessibility refers to the ease of grasping a part by hand or a tool for removal (Soh et al., 2015). Consider the Z-axis dimension of a component, where the accessibility (Refer to Figure 7) increases with the exposed dimension or ‘ΔZ’ of the component relative to its total dimension in the Z-axis given by ‘Z’ (Soh et al. 2015).

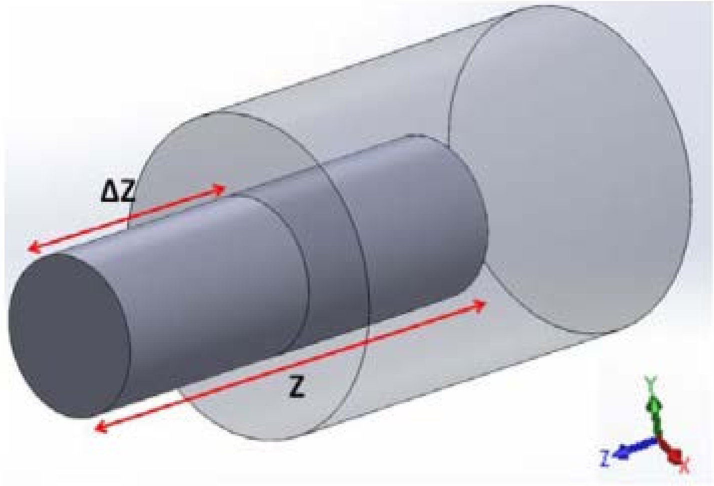


Figure 7 Part Accessibility Illustration (Soh et al., 2015)

When disassembling a product, whether a component is accessible or not affects the ease of disassembling. Thus, the factor of dimensional access for the component in the X, Y and Z-axis respectively can be used to assess the overall component accessibility. Based on this factor, Soh et al. (2015) proposes a part accessibility assessment metric (I_{acc}) to evaluate how easily a part can be grasped by a hand or a tool during the disassembly. It is shown in Equation (11).

$$I_{acc} = -\left[log_2\left(\frac{\Delta X}{X}\right) + log_2\left(\frac{\Delta Y}{Y}\right) + log_2\left(\frac{\Delta Z}{Z}\right)\right] \tag{11}$$

where,

I_{acc} – Component Accessibility rating

ΔX, ΔY, and ΔZ – part accessible ranges along X, Y, and Z axes, respectively.

X, Y, and Z – largest dimensions of part along X, Y, and Z axis, respectively.

In this research work, Component Accessibility rating from this point onwards, will be represented by the notation 'a_N'. Here, 'N' is the total number of components and 'a_N' represents the component specific accessibility rating for the N^{th} component. Soh et al. (2015) then proposes the multiplication for 'a_N' of each component with its respective quantity in the BOM. Doing so gives the adjusted accessibility rating for each component which can be represented by 'A_N'. One limitation of Equation (11), is that it lacks an upper limit to the 'A_N' making it difficult to assess whether the optimal accessibility is obtained or not. This is a limitation since the intended goal is to establish a metric that assesses the actual state of the product design aspect and returns a score between '0' and '1' as mentioned earlier [see section 3.2.1]. To address this, a simple metric is proposed to rate the 'A_N' against a scale, which is formed by determining the minimum and maximum 'A_N' among all the components of the product under consideration. The proposed metric for **A_N'** is shown in Equation (12).

$$\boxed{A_N{}' = 1 - \left[\frac{A_N - Min.\ A_N}{Max.\ A_N - Min.\ A_N}\right]} \tag{12}$$

where,

A_N' – Score for the N^{th} Component

A_N – N^{th} Component's adjusted accessibility rating.

Min. A_N – Minimum A_N

Max. A_N – Maximum A_N

Equation (12) rates the individual components against the minimum and maximum limits established by the corresponding values of A_N. This ensures a relative scoring, as the minimum and maximum limits can vary greatly between different products. The scoring for each component is done on a scale of '0' to '1', where '1' refers to the highest accessibility and 0 represents the lowest accessibility. After all the A_N' are determined, an average is taken to give an overall score for the Product's accessibility represented by 'PA'. The proposed metric for 'PA' is shown in Equation (13).

$$\boxed{PA = \frac{[\sum_1^N (A_N{}')]}{N}} \tag{13}$$

where,

PA – Product accessibility

3.3 PHASE II: Process Technology Assessment

In this research, we use the term 'Process Technological Capability for Disassemblability (PT_D)' to represent the ability to disassemble a product based on the capability of the process technology used. It is proposed that 'PT_D' be built upon two aspects: 1. Disassembly Score (**D**), and 2.

Disassembly Effort Index (**E_D**). 'D' and 'E_D' will be discussed in the sections 3.3.1 and 3.3.2 respectively. Whereas, 'PT_D' itself will be discussed in the section 3.5.2. Figure 8 shows the methodology for the process technology assessment during disassembly process.

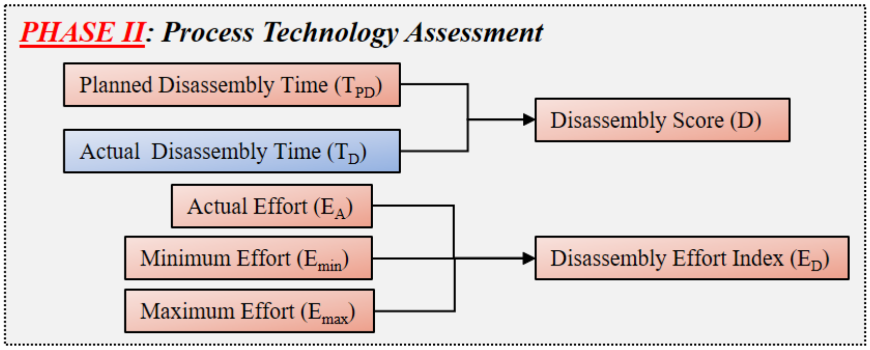


Figure 8 Methodology for Process Technology Assessment

3.3.1 *Disassembly Score (D)*

In this research, disassembly process is proposed to have been affected by two sub-aspects of the process technology, namely 'D' and 'E_D'. The amount of time consumed during disassembly is an indication of the disassembly cost, but this is not completely relevant. Since, different products might have different number of components thereby having varying disassembly times. Hence, it is possible to establish a standard disassembly time for each product based on its design. This is nothing but the Planned Disassembly time (T_{PD}) which is reasonable to consider. It is also realistic to consider that the disassembly process itself might have set backs and so experience longer lead times. Such setbacks could be due less skilled operators, tool failure, machine breakdown, etc. The result in the end is the deviation from the planned time. In this research, it is proposed that this deviation be used to convey the effect of disassembly time on the disassemblability of the product. Before that, let's have look at the proposed metrics and their limitations found in the previous studies. Disassembly time has already been considered by Bras and Hammond (1996) as one of the process related factors that affect disassemblability. In fact, the work in this thesis is inspired from their proposed metrics. The metric '$m_{disassembly}$' proposed by Bras and Hammond (1996) is shown in Equation (14).

$$\boxed{m_{disassembly} = \frac{(\#Ideal)(1.5sec)}{Time_D}} \tag{14}$$

where,

#Ideal – Theoretical Part Count

$Time_D$ – Actual disassembly time

Equation (14) is based upon the Design-for-Assembly (DFA) principles (Bras & Hammond, 1996). As per the DFA principles, 3 seconds is allotted per ideal part for reassembly (Bras & Hammond, 1996). As disassembly is often much faster than assembly, the DFA analysis can be modified to allocate only 1.5 seconds per ideal part (rather than 3 seconds) for disassembly (Bras & Hammond, 1996). The limitation of this approach is that during disassembly not all the companies may have access to the theoretical part count of the product. This is especially a challenge if a 3rd party remanufacturing company is involved in performing the disassembly and/or remanufacturing. Further, not all the disassembly operations may take 1.5 seconds. Some might take longer, and few might take shorter amount of time, thus it's hard to standardize the time for all the product. Thus, it is proposed that the deviation of the actual disassembly time ($Time_D$) from the planned disassembly time ($Time_{PD}$) be considered to capture the effect of disassembly time on the product disassemblability.

Also, as opposed to the theoretical part count, data regarding the planned disassembly time is more easily available for an organization, be it the OEM or a 3rd party remanufacturer. This is because they are already performing the disassembly process and thus, will have an ideal or planned scenario that acts as a benchmark of assessment for the current scenario. Considering the reasoning presented above, it is more realistic to capture the information generated by the comparison of the '$Time_{PD}$' and '$Time_D$', for product disassemblability. If the actual time is greater than the planned time, that implies the actual process is slower than what it should be and hence, is costing the company more. Such unexpected loss impacts the overall profit. In some cases, where the product has a low profit margin, such a loss can make the disassembly process economically infeasible. Hence, a new metric is proposed that compares the planned and actual disassembly times. This metric is shown in Equation (15).

$$\boxed{D = 1 - \left(\frac{Time_D - Time_{PD}}{Time_{PD}}\right)} \tag{15}$$

where,

D – disassembly time score

$Time_{PD}$ – Planned disassembly time

The proposed metric in Equation (15), is accompanied along with three boundary conditions/limitations where, if $x = \text{Time}_D$ and $y = 2*(\text{Time}_{PD})$, then,

- If, $x < y$, then, $D = 1$
- If, $x > 2y$, then, $D = 0$
- If, $2y > x > y$, then, D is between ‘0’ & ‘1’.

3.3.2 *Disassembly Effort Index (E_D)*

Disassembly Effort required during the disassembly is another widely discussed factor (Desai & Mital, 2003) (Shu & Flowers, 1999) in the previous studies which has a significant influence on the product disassemblability. While disassembling, various steps must be followed to facilitate the step-by-step removal of all the components. This requires different tools in different positions, core setups, etc. The handling or effort invested in performing these tasks is referred to as the disassembly effort (Desai & Mital, 2003). This is different than the unfastening effort discussed under the fastener complexity (refer to Section 3.2.1). The U-rating only captures the complexity of different types of fasteners and does not consider the handling effort required for setting up the core and using different tools during disassembly. Earlier work by Desai and Mital (2003) presents a scoring system for the analysis of disassemblability. The intent of this scoring scheme is to assess the product disassemblability from the disassembly effort point of view. The work presented by Desai and Mital (2003) can be found in Appendix C.

This scoring scheme considers different criteria of operator handling such as: 1. Disassembly force, 2. Material Handling, 3. Tools required, 4. Accessibility of joints/grooves, and 5. Positioning of Tool (Desai & Mital, 2003). Given the comprehensiveness of the scoring scheme, the effort required during the disassembly process can be assessed in detail. In this research, it is proposed that this scheme be used to score all the different steps involved in the disassembly of the product. The scores for all steps can then be aggregated to obtain a value for the actual effort required (E_A) during the product disassembly.

The scoring scheme under each of the above criteria, has a minimum possible and a maximum possible score (Desai & Mital, 2003). Assigning all the steps with the maximum aspect scores and then aggregating will give the maximum possible effort score required ($E_{DMax.}$) during the product disassembly. This means, if the process is made to be more cumbersome, the worst possible situation would be indicated by E_{DMax}. Similarly, to have the best scenario, the minimum effort should be used for disassembly. For this, the lowest aspect scores can be assigned for each of the disassembly step and then aggregated to give the minimum possible effort score ($E_{DMin.}$). Based on

'E_{DA}', '$E_{DMax.}$', and '$E_{DMin.}$', a metric 'E_D' is proposed which is shown in Equation (16). By doing so, the current disassembly process can be evaluated to determine whether it is more physically demanding, or not.

$$\boxed{E_D = 1 - \left[\frac{E_{DA} - E_{DMin}}{E_{DMax} - E_{DMin}}\right]} \qquad (16)$$

where,

E_D – Disassembly Effort Index

E_{DA} – Actual Effort Score for disassembly

$E_{DMax.}$ – Maximum Effort Score for disassembly

$E_{DMin.}$ – Minimum Effort Score for disassembly

Based on the Equation (16), E_D always ranges between 0 to 1, where '0' implies that the disassembly process is very physically challenging and '1' means the disassembly process requires the lowest amount of effort by the operator. Earlier, Figure 5 was presented to show the intended relationship between the proposed metrics and the underlying factors. Considering the discussions presented for each of the proposed metrics under the process technology assessment, it is reasonable to accept the intended relationships as illustrated in Figure 5.

3.4 PHASE III: Incoming Quality Assessment

The time and resources required for the disassembly process depend significantly on the incoming quality of the returned product. If the quality is not acceptable, replacement of some components and, in some cases, rejection of the entire product can occur. The importance of this information in context of disassemblability has not been considered in the previous studies. In this research, phase III attempts to capture this information by proposing a metric known as '$\mathbf{Q_D}$'. Figure 9 illustrates an overview of the methodology for the incoming quality assessment.

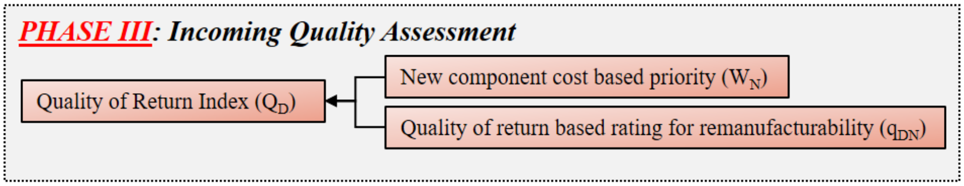


Figure 9 Methodology for Incoming Quality Assessment

When the incoming quality is poor, only partial disassembly may be feasible; if the quality is not adequate, sometimes no disassembly will occur. Hence, despite the availability of disassembly facilities, the disassembly of the product can be limited due to its incoming quality. The effect of incoming quality on the disassemblability of a product has been discussed in few studies (Bhattacharya & Kaur, 2015) (Ferguson, 2009), but no explicit metric has been proposed to quantify this information. Hence, to evaluate the incoming quality at the product level, a new metric denoted by 'Q_D' is proposed in this research.

To quantify this aspect, a simple metric is proposed, where, the components are rated on a binary scale a value of 0 or 1 based on the return quality. A value of '1' implies that the component is of an acceptable quality and '0' is assigned if the component is rejected and replaced due to bad quality or OEM guidelines. One way of aggregating the ratings of all the components would be to take an average which can be misleading, since, averages are sensitive to extreme values. As this a binary scale, averaging approach will result in misinformation. Also, realistically the scores should favor the more costlier components. Reason being, such components usually have greater priority over the cheaper ones. To address this issue, the concept of cost based QOR is introduced. This means that each component is assigned with a cost based relative weight with respect to the total price of the product. The component specific weights along with their respective ratings are aggregated by the proposed metric shown in Equation (17).

$$\boxed{Q_D = \left(\sum_{1}^{N} q_{DN}\, w_N\right)} \tag{17}$$

where,

Q_D – Quality of return index for disassemblability

N – Total number of components

q_{DN} – Binary rating for the N^{th} component (0 – rejected & replaced, and 1 - accepted) during disassembly

w_N – Relative cost based weight for the N^{th} component

Here, the 'c_N' is assessed by the proposed metric shown in the equation (18).

$$\boxed{w_N = \left(\frac{c_N}{\sum c_N}\right)} \tag{18}$$

c_N – new cost of Nth Component

$\sum c_N$ – New product cost

'Q_D' always ranges between 0 and 1 where, '1' implies the best incoming quality and '0' means all the non-fasteners have been rejected and replaced. Hence, the proposed relationship between component cost, and incoming quality as per Figure 5 have been established.

3.5 PHASE IV: Consolidated Index Development

The consolidation of metrics to compute an index with a value between '0' and '1'is presented here. The reason is to provide the user with a single value that represents the quantification of various underlying sub-metrics considered for the product design, process and incoming quality aspects. Figure 10 gives an overview of the methodology for the Phase IV.

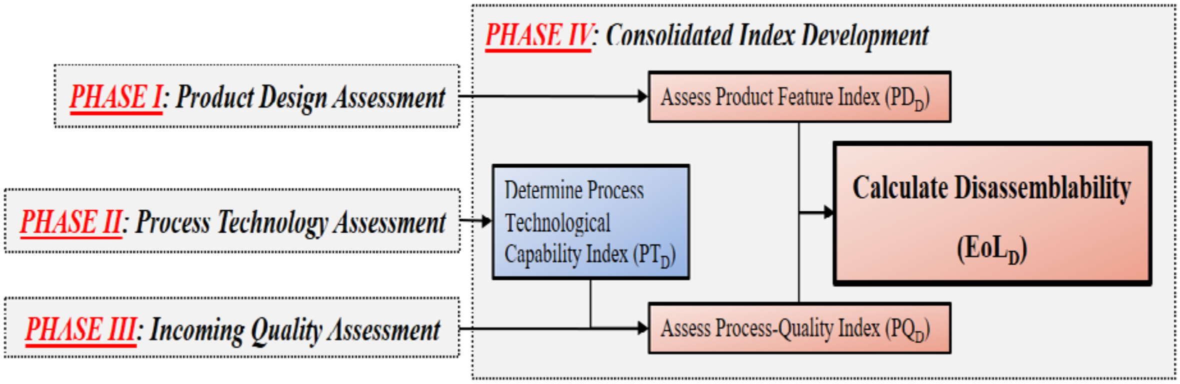


Figure 10 Methodology for Consolidation of Index

Consolidated Index that will be discussed in the upcoming sections are as follows:

1. Product Feature Index for Disassemblability (PD_D)
2. Process Technological Capability (PT_D)
3. Process-Quality Index (PQ_D)
4. Disassemblability (EoL_D)

3.5.1 *Product Feature Index for Disassemblability (PD_D)*

The ‘PC_D’ and ‘PA’ metrics described in the sections 3.2.1 and 3.2.2 respectively, can be integrated to provide a single metric to provide an overall assessment of the product design in terms of the ability to disassemble a product. One way of combining accessibility and complexity metrics would be to determine their mean which is not advisable (Soh et al., 2015). It is so because, the arithmetic average is extremely sensitive to extreme values determining the mean. Hence, another option is to use a combination metric known as the F-measure (Amigó et al. 2011). The standard format for the F-measure metric as proposed by Amigó et al. (2011) is shown in Equation (19). Here, R and P are the example metrics to be integrated and α is the relative weight of the metrics.

$$\boxed{F(R,P) = \frac{1}{\alpha(\mathrm{R})^{-1} + (1-\alpha)(\mathrm{P})^{-1}}} \tag{19}$$

In this research, it is proposed that Equation (19) be used for combining PC_D and PA to give a single index. Similar approach for aggregation is utilized in the previous work of Soh et al. (2015). To give equal weightage to PC_D and PA, value of ‘α’ value is set at 0.5. In this manner both PC_D and PA will carry the same weight (= 0.5). The Product Feature Score for Disassemblability (PD_D) is obtained by integrating PC_D and PA by using the F-measure metric, with ‘α’ = 0.5, is shown in Equation (20).

$$\boxed{PD_D = \frac{2}{(Pc_D)^{-1} + (\mathrm{PA})^{-1}}} \tag{20}$$

3.5.2 *Process Technological Capability for Disassemblability (PT_D)*

Bras and Hammond (1996) propose a combinatorial metric ‘$m_{\mathrm{Remanufacturability}}$’, that attempts to integrate seven process related aspects into a single score. This metric is based on an inverse weighted addition technique which is a non-linear additive approach and satisfies the annihilation criterion. The annihilation criterion ensures that if one metric approaches zero, the remanufacturability index also will approach zero - regardless of the performance of the other indices (Bras & Hammond, 1996). This is done to ensure that a significant problem which would make a product extremely difficult to remanufacture would not be overshadowed by outstanding performance in other areas (Bras & Hammond, 1996). This proposed metric by Bras and Hammond (1996) is shown in Equation (21).

$$m_{Remanuacturbaility} = \left(\sum_{x=1}^{7} \frac{w_x}{\mu_x} \right)^{-1} \tag{21}$$

where,

W_e – investment based weights for each process related factor

μ_x – process related score

Process Technological Capability Disassembly (PT_D) is an integrated metric based on ‘D’ and ‘E_D’. Such integration is useful in providing the user with a single index that represents the impact of both the metrics ‘D’ and ‘E_D’. It is important to mention that even F-measure can integrate two metrics, but it is not used here. This is because, while integrating the process related aspects, the weighting is established by the help of a prioritization matrix. In case of F-measure, prioritization matrix is not used. Also, the proposed metric for ‘PT_D’ has the capability to integrate two or more aspects which is not the case of F-measure. Thus, the same metric can be applied in the case of remanufacturability when the process related aspects increase from two (in the case of disassemblability) to five. This is not possible to achieve via the F-measure metric. Also, to be able to apply similar metrics improves the ease of implementation of the methodology from the user’s point of view. Another difference of application observed in previous literature was that F-measure integrate scores across different classification of aspects (*i.e.* product design and process-quality; quality of return index and process technological capability, etc.). Whereas, the proposed metric for ‘PT_D’ is used for integration of internal scores from the metrics of the same aspect. For example, process related aspects and its two metrics.

A modified form of Equation (21) is proposed where the combinatorial metric integrates only two instead of seven metrics. The proposed metric for ‘PT_D’ is shown in Equation (22),

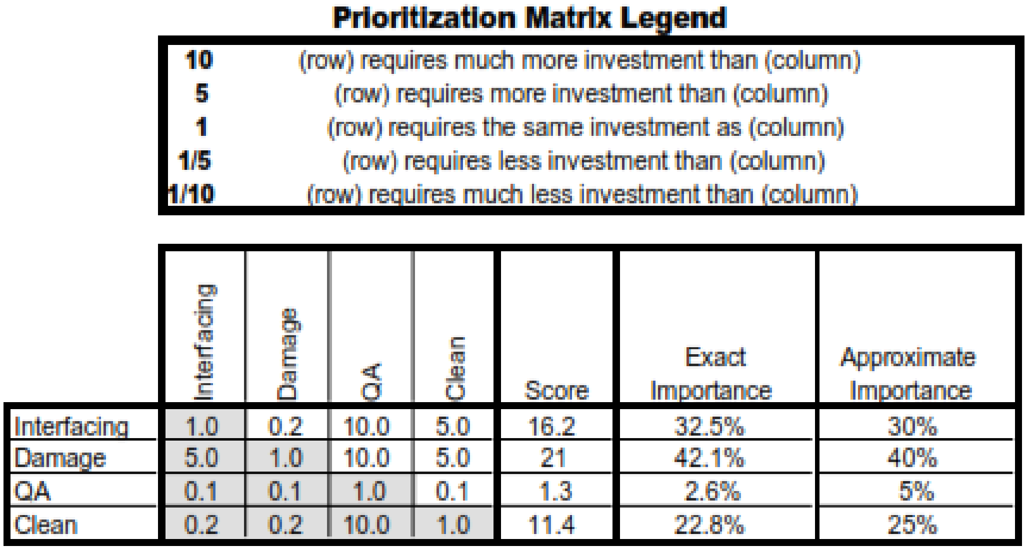
$$PT_D = \left(\sum_{l=1}^{2} \frac{w_x}{v_x} \right)^{-1} \tag{22}$$

where,

W_x = Weights based on relative investment such that, $W_{1} = W_D$ and $W_2 = W_{ED}$

V_x= Scores for different process related aspects such that, V_1 = D and $V_2 = E_D$

The weights ‘W_D’ and ‘W_{ED}’ are established using a prioritization matrix to determine a relative weighting scheme for the both the categories. Based on the feedback from the remanufacturers, both the ‘D’ and ‘E_D’ are compared based on the investment involved. The comparison leads to relative weights with the help of a prioritization matrix. An example of a prioritization matrix is shown in the Figure 11.



Prioritization Matrix Legend

10	(row) requires much more investment than (column)
5	(row) requires more investment than (column)
1	(row) requires the same investment as (column)
1/5	(row) requires less investment than (column)
1/10	(row) requires much less investment than (column)

	Interfacing	Damage	QA	Clean	Score	Exact Importance	Approximate Importance
Interfacing	1.0	0.2	10.0	5.0	16.2	32.5%	30%
Damage	5.0	1.0	10.0	5.0	21	42.1%	40%
QA	0.1	0.1	1.0	0.1	1.3	2.6%	5%
Clean	0.2	0.2	10.0	1.0	11.4	22.8%	25%

Figure 11 Prioritization of Metric Categories (Bras & Hammond, 1996)

Bras & Hammond, (1996) establish the prioritization matrix by subjectively allotting the fractional weights. It would be more realistic to considers the investments directly. That way, cheaper activities will lose priority and the highest weight will be given to the costliest activity. In this research, it is proposed that the ratios be taken for the exact investment amounts where in manner of ‘row vs column’. Then, the ratios are aggregated horizontally from left to right to establish an activity wise score. Next, these scores are aggregated from top to bottom, which is then used to establish relative weights for each activity.

3.5.3 *Process-Quality Index for Disassemblability (PQ_D)*

As per the previous studies, the incoming quality of products significantly impacts the disassemblability of a product (Bhattacharya & Kaur, 2015) (Ferguson, 2009). Generally, the purpose of disassembly is to enable remanufacturing, reuse or recycle of the non-fasteners (Aydin et al., 2017) (Bras & Hammond, 1996). If the incoming quality is unacceptable for reuse, remanufacture or recycle then conducting the disassembly is futile. Thus, given the QOR, the product or its components could be rejected thereby halting the disassembly process, even though the process is completely technologically capable. This limitation imposed by the QOR is not addressed explicitly by any metric in the previous studies. In this research, to capture the limitation imposed by QOR on 'PT_D', a metric 'PQ_D' is proposed and shown in Equation (23).

$$\boxed{PQ_D = PT_D * Q_D} \tag{23}$$

where,

PQ_D – Process-Quality Index

PT_D – Process technological-capability for disassembly

'PT_D' always returns a value between '0' and '1', where '0' means highest limitation on product disassemblability due to QOR. And '1' implies highest product disassemblability due to best incoming QOR.

3.5.4 *Disassemblability (EoL_D)*

As discussed earlier, Disassemblability is enabled by various factors and metrics (refer sections 3.1 to 3.4). All the factors considered from the aspects of product design, process technology and incoming quality in this research work, have not been considered before. That is why this quantitative methodology is unique than the previous studies. The underlying factors when assessed quantitatively, have multiple results that can confuse or mislead the user. Having a single integrated result that reflects the impact of all the underlying metrics makes it easy for the user to follow. Hence, a combinatorial metric based on Equation (19) is proposed to integrate the scores of 'PQ_D' and 'PD_D' metrics into a single value of 'EOL_D'. The proposed metric 'EOL_D' is shown in Equation (24). The value of 'α' in this case is again set at 0.5, so that both 'PQ_D' and 'PD_D' get equal weights.

$$\boxed{EoL_D = \frac{2}{(PD_D)^{-1} + (PQ_D)^{-1}}} \tag{24}$$

where,

EoL_D - Disassemblability

3.5.5 *Analytical model for EoL$_D$*

Analytical model in this research work is defined as the model that addresses the interaction of all factors discussed in Chapter 3. Using the proposed methodology, to assess the EoL$_D$ can be further simplified and expressed in the form of the underlying sub-metrics. Doing so, makes it easier for the user to apply the above methodology in a more succinct manner. The simplified version of Equation (24) will be obtained by substituting Equations (20), (22), and (23) in a step by step approach.

Step 1: Substituting Equation (20) in Equation (24), we get,

$$\boxed{EoL_D = \frac{2 * Q_D * PT_D * PD_D}{Q_D * PT_D + PD_D}} \tag{25}$$

Step 2: Substituting Equations (22) and, (23) in Equation (25), we get,

$$\boxed{EoL_D = \frac{4 * Q_D * [(D * E_D)/(E_D * W_D + W_{ED} * D)] * [(PC_D * PA)/(PC_D + PA)]}{Q_D * [(D * E_D)/(E_D * W_D + W_{ED} * D)] + [2 * (PC_D * PA)/(PC_D + PA)]}} \tag{26}$$

Step 3: Further simplifying Equation (26), we get,

$$\boxed{EoL_D = \frac{PC_D PA Q_D D E_D}{[0.25 * (PC_D + PA) * (Q_D D E_D)] + [0.5 * (PC_D PA) * (E_D W_D + W_{ED} D)]}} \tag{27}$$

Step 4: Further simplifying Equation (27), we get Equation (28), which is the final form of the leading function for Disassemblability (EoL$_D$):

$$\boxed{EoL_D = [\Big(0.25 * (PA^{-1} + PC_D^{-1})\Big) + (0.5 * Q_D^{-1} * (W_{ED} D^{-1} + W_D E_D^{-1})]^{-1}} \tag{28}$$

Chapter 4 Methodology for Remanufacturability Assessment

This chapter proposes a methodology for remanufacturability assessment which is based on the factors identified in Table 3 (see chapter 1). Product disassembly as one of the sub-processes required for remanufacturing (Aydin et al. 2017). Thus, some of the factors and metrics used for assessing remanufacturability are like those used for disassemblability. The origin and the classification of these factors have been discussed briefly in the literature review. Figure 12 provides an overview of the proposed methodology for remanufacturability assessment. Like the steps in quantifying disassemblability, this assessment has also been broken down into four phases.

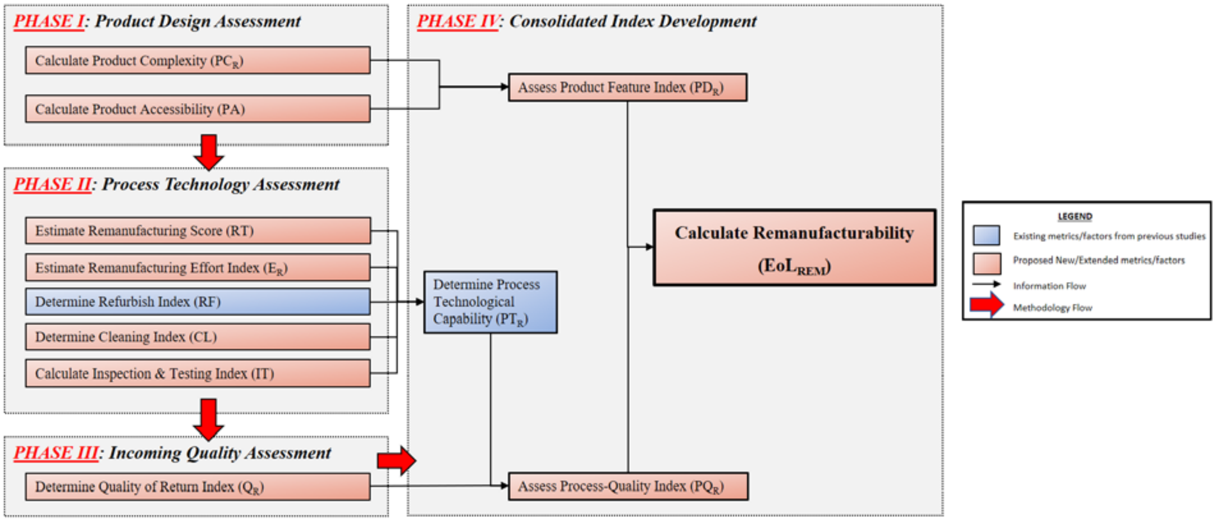


Figure 12 Methodology of Remanufacturability Assessment

The first proposed phase assesses the product design related characteristics and is represented by the Product Feature Index for Remanufacturability (PD_R). The next phase considers the assessment of process related technological capability. This phase consists of five sub-aspects as compared to two in the case of 'PT_D' assessment. Third phase of the methodology asses incoming quality of the returned product through a quality grading metrics. This aspect considered is based on the limitation that is imposed on the remanufacturability of a product due to unacceptable quality of the components. Lower or unacceptable quality of returns can make a fully capable remanufacturing process redundant. Whereas, an outdated remanufacturing process (in terms of technology and practice) can have the same effect on the products remanufacturability irrespective of the best possible incoming quality.

Factors Proposed Metrics	Number of Fastener types	Number of each type of fasteners	Unfastening Difficulty for each fastener type	Number of total components	Disassembly Time	Remanufacturing Effort	Labor Cost	Setup and Tool Cost	Quality of Returns	Dimensional Access of Components	Degree of freedom of Components	Number of Inspected Components	Total non-fastener count	Assembly & Refurbish time	Cost of Cleaning Activities	Testing Time	No. of Refurbished Components	Cost of New Component	Status	Source
Product Complexity	X			X									X						New metric	-
Non-Fastener Complexity												X	X					X	New metric	-
Fastener Complexity	X	X	X	X															Modified metric	Fang et al. 2015, Das & Naik (2002)
Product Accessibility										X	X								New metric	-
Remanufacturing Score					X			X						X					Modified metric	Bras & Hammond (1996)
Remanufacturing Effort Index						X	X	X											Modified metric	Desai & Mittal (2003)
Quality of Return Index				X					X									X	New metric	-
Refurbish Index								X									X		Original metric	Bras & Hammond (1996)
Cleaning Index								X							X				Modified metric	Bras & Hammond (1996)
Inspection & Testing Index							X	X				X				X			Modified metric	Bras & Hammond (1996)

Figure 13 Metrics proposed for remanufacturability assessment

4.1 Identification of Metrics

Capability to remanufacture a product depends on various factors identified in Table 3, some more relevant than others. This table is a shortlisted from Appendix C in a similar manner adapted in the case of disassemblability. A group of metrics is proposed that are explicitly based on these factors. Reasoning behind each metric will be discussed along with their introduction in the upcoming sections. Figure 13 gives a brief overview of the intended relationships between the proposed group of metrics and the identified factors.

Figure 13 also shows if the proposed metric is borrowed and extended or, if originally proposed in this research. Various metrics build upon different or similar form of collected data to give quantification of different aspects of remanufacturability and hence, end up sharing one or more factors. It should be noted that this list of factors longer compared to the list considered for disassemblability. This is understandable because product remanufacturing consists of various sub-processes including disassembly. And as a result, several proposed metrics for remanufacturability are like disassemblability.

4.1.1 *Similarities between Disassemblability and Remanufacturability*

Let's assume that a user needs to assess both the 'ilities' together, in that case the combined methodology will appear to be like the overview given in Figure 14. This figure attempts to compare the methodology of both the 'ilities' by differentiating the metrics based on their border format. All the metrics highlighted in solid red border are the common or shared metrics between both the 'ilities'. This means along with the concept; the results are also shared. Whereas, all the metrics highlighted in dashed red border, only share the concept but not the results. This implies that such metrics have the same construction for both the 'ilities' but process different values. For example, final consolidation metrics 'EoL_D' and 'EOL_{REM}' integrate two scores but the values for product feature index and process-quality index are different for both the 'ilities'. The third set of differentiated metrics are highlighted in purple border. These are unique to remanufacturability assessment as they are not considered for disassemblability, *i.e.* Inspection & Testing Index, Refurbish Index, etc.

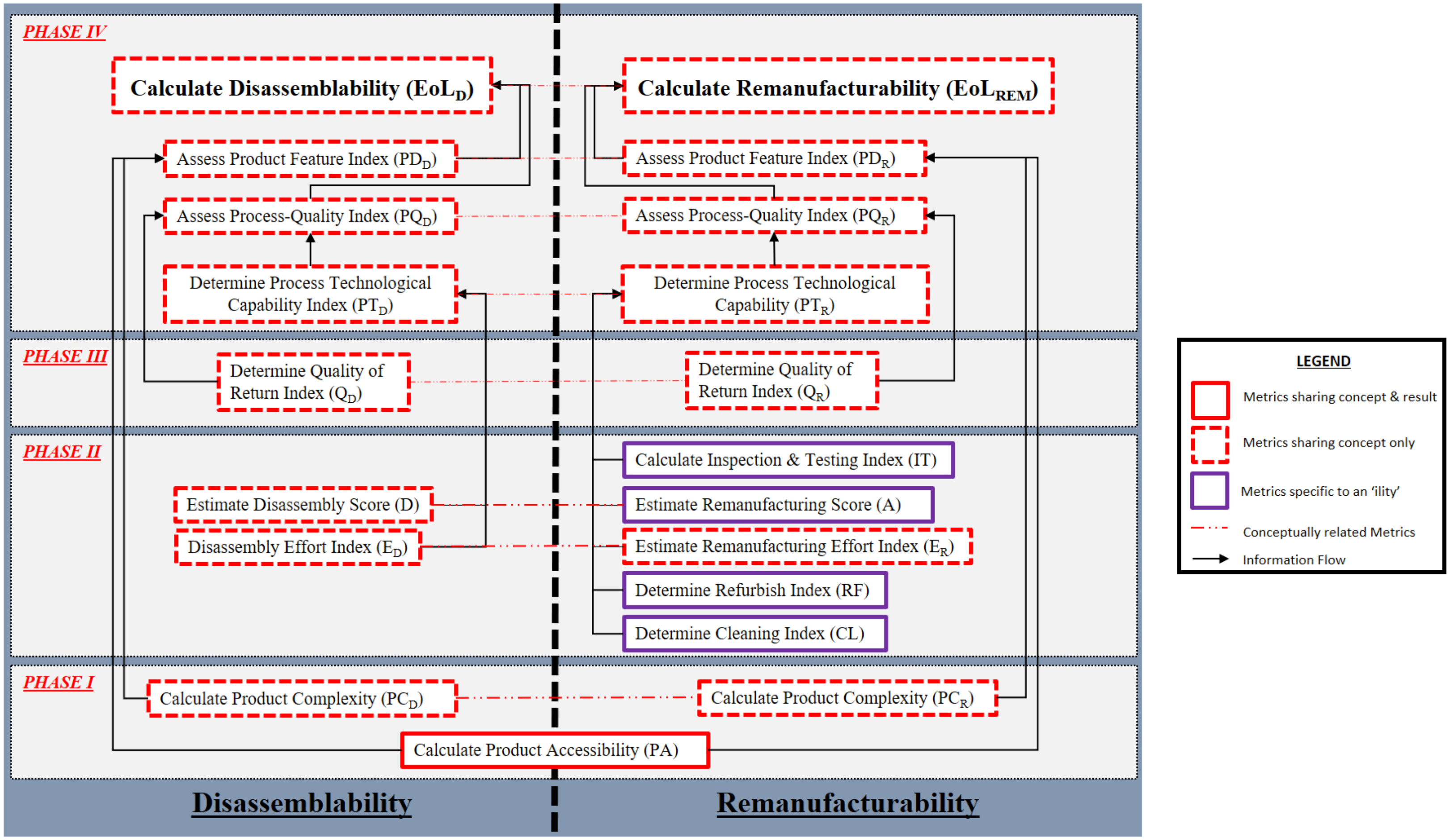


Figure 14 Combined Methodology of Remanufacturability and Disassemblability

It is important that Figure 14 be understood since the upcoming sections only discuss the metrics highlighted in purple and dashed red borders but not the ones highlighted in solid red borders.

4.2 PHASE I: Product Design Assessment

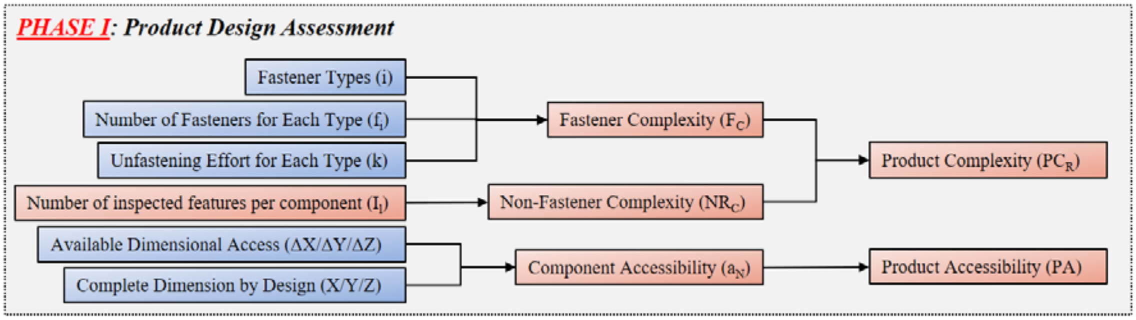


Figure 15 Methodology for Product Design Assessment

Product Feature Index for Disassembly (PD_R) represents the ease with which the product can be remanufactured based on its design characteristics. 'PD_R' builds upon two sub-metrics known as, 1. Product Complexity for remanufacturability (PC_R), and 2) Product Accessibility (PA) as shown in Figure 15. These sub-metrics are discussed further in sections 4.2.1 and 4.2.2 respectively. But the metric for 'PD_R' is discussed in the section 3.5.1.

4.2.1 *Product Complexity for Remanufacturability (PC_R)*

In this research work, 'PC_R' represents the ease with which the product can be remanufactured based on the fastener and non-fastener complexity. The fastener complexity is the same during the disassembly and remanufacturing. But that's not the case with the non-fastener complexity. The complexity brought about by thorough inspections activities of critical non-fastener components is captured by the metric 'Non-Fastener Complexity during remanufacturing (NR_C)'.

Fastener Complexity (F_C)

'F_C' is the same for disassemblability and remanufacturability because the fastener details remain the same during disassembly and remanufacturing. Their count or difficulty in unfastening does not change between both the 'ilities'. Hence, please see section 3.2.1 for further details.

Non-fastener Complexity during Remanufacturing (NR_C)

Like Disassembly, remanufacturing also involves inspection activities for some critical dimensions of certain critical non-fasteners. As discussed earlier (see section 3.2.1), this adds to the complexity of the process since, this requires more awareness, and better auditing skills from the operator onsite. Although, in the case of remanufacturing, all the components are completely disassembled making thorough inspection procedures for non-fasteners possible. Hence, generally, more number of components and more number of features inspected during remanufacturing as compared to disassembly. Considering the features which are available, all of them may or may not be inspected as per the OEM guidelines. But often, it is the costlier set of non-fasteners that are usually inspected thoroughly. Thus, the factors like the count and the cost of non-fasteners play an important role in determining the remanufacturability from the perspective of non-fastener complexity. Let's assume:

1. the number of inspected non-fasteners during remanufacturing be given by 'u'.
2. the no. of available features for inspection of uth non-fastener during remanufacturing be given by 'T_u'.
3. the no. of inspected features of uth non-fastener during remanufacturing be given by 'I_u'.
4. the cost of the inspected uth non-fastener be given by 'C_u'.
5. the cost based weight for the inspected of uth non-fastener during remanufacturing be given by 'W_u'

Hence, the proposed metric of 'NR_C' is shown in Equation (25).

$$\boxed{NR_C = \left[\sum_{1}^{u}\left(1-\left(\frac{I_u}{T_u}\right)\right) * W_u\right]} \tag{29}$$

where,

'W_u' is assessed by the proposed metric shown in Equation (26).

$$\boxed{W_u = \frac{C_u}{\sum C_u}} \tag{30}$$

To derive a complexity score for the complete product, a weighted addition for NR_C and F_C is proposed like 'PC_D'. By using the weights z_1 and z_2 (Refer to Equation (8), (9), and (10)), skewing the overall complexity score towards either non-fasteners or fasteners is avoided. The proposed new metric for the Product Complexity for remanufacturability (PC_R) is given by Equation (27).

$$\boxed{PC_R = (z_1 * NR_C) + (z_2 * F_C)} \tag{31}$$

Figure 13 earlier was presented to show the intended connection between the proposed metrics and the underlying identified factors in Table 3.

4.2.2 *Product Accessibility (PA)*

'PA' remains constant for both the 'ilities' since it is a dimension dependent metric which is measured during the disassembly stage. This stage is identical for both disassembly and remanufacturing process. Details for 'PA' can be found in the section 3.2.2.

4.3 PHASE II: Process Technology Assessment

In this research, we use the term 'Process Technological Capability for Remanufacturability (PT_R)' to represent the ability to remanufacture a product based on the capability of the process technology used. It is proposed that 'PT_R' be built upon 6 sub-metrics:

1. Remanufacturing Time Score (**RT**),
2. Remanufacturing Effort Index (**E_R**),
3. Refurbish Index (**RF**),
4. Cleaning Index (**CL**),
5. Inspection and Testing Index (**IT**)

All the above five sub-metrics will be in the sections 4.3.1, 4.3.2, 4.3.3, 4.3.4, and 4.3.5 respectively. Whereas, 'PT_R' will be discussed in the section 4.5.2. Figure 16 shows the proposed methodology for the process technology assessment during the remanufacturing process.

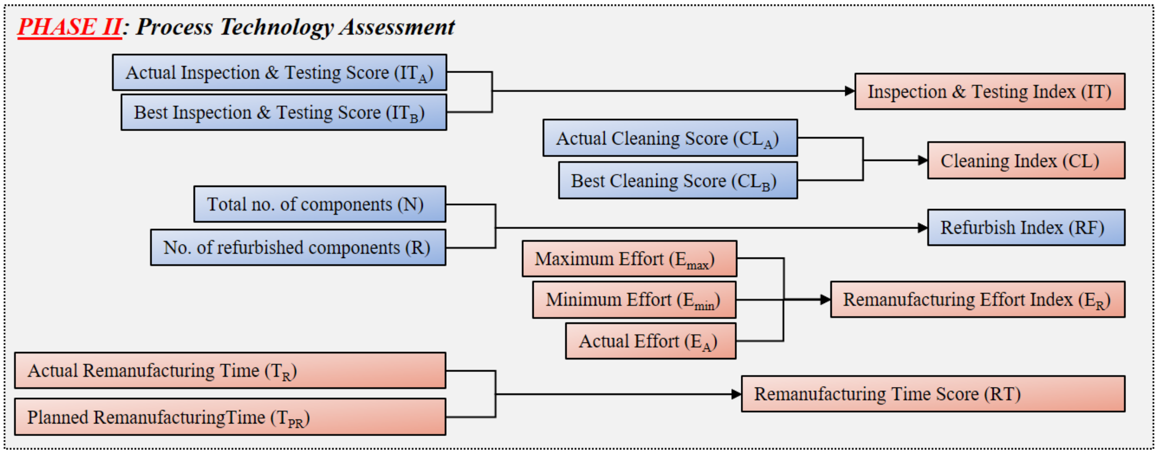


Figure 16 Methodology for Process Technology Assessment

4.3.1 *Remanufacturing Score (RT)*

In this research, remanufacturing process is proposed to have been affected by five sub-metrics of the process technology. Effect of time used while disassembling and assembling a product on the remanufacturability has been widely discussed in the literature. The metric '$m_{assembly}$' proposed by Bras and Hammond (1996) is shown in Equation (28).

$$\boxed{m_{assembly} = \frac{(\#Ideal)(3sec)}{Time_A}} \quad (32)$$

where,

#Ideal – Theoretical Part Count

$Time_A$ – Actual assembly time

Like Equation (14), Equation (28) is based upon the DFA principles (Bras & Hammond, 1996). On the basis of the DFA principles, 3 seconds is allotted per ideal part for reassembly (Bras & Hammond, 1996). There are two limitations to this approach that have been discussed in the previous section (see section 3.3.1). Moreover, the same study proposes metrics to capture the effect of number of refurbished components but does not consider the effect of refurbishing time. Bras & Hammond, (1996) also propose metrics for cleaning and inspection that capture the effect of time and investment behind them. These are further discussed in detail under sections 4.3.4 and 4.3.5. As they already consider the effect of time, remanufacturing time for this study only considers the disassembly, assembly and refurbishing time. The remanufacturing time is a strong indication of the remanufacturing cost, which could be unique to a specific product. Hence, it is possible to establish a planned remanufacturing time for each product based on its design and the planned process flow. This is can be represented as the 'Planned Remanufacturing Time (T_{PR})' which is reasonable to consider.

In this research like disassembly score (D), it is proposed that this deviation of the actual remanufacturing time (T_{RT}) from the planned remanufacturing time be considered to capture the effect of disassembly, assembly and refurbishing time on the product remanufacturability. Ease of data collection regarding the planned and actual remanufacturing time are similar to section 3.3.1. Since, be it an OEM or a 3rd party remanufacturer, they will be performing the remanufacturing process themselves. Hence, will have easy access to planned and actual time data. Considering the above discussion, a metric is proposed that compares the planned and actual remanufacturing times. This metric is shown in Equation (29).

$$\boxed{RT = 1 - \left(\frac{Time_{RT} - Time_{PRT}}{Time_{PRT}}\right)} \tag{33}$$

where,

RT – Remanufacturing time score

$Time_{RT}$ – Actual remanufacturing time; $Time_{PRT}$ – Planned remanufacturing time

The proposed metric in Equation (29), is accompanied along with three boundary conditions/limitations where, if $\alpha = Time_{R}$ and $\beta = Time_{PR}$, then,

- If, $\alpha < \beta$, then, D = 1;
- If, $\alpha > 2\beta$, then, D = 0
- If, $2\beta > \alpha > \beta$, then, D is between '0' & '1'.

4.3.2 *Remanufacturing Effort Index (E_R)*

Effort required during the remanufacturing has not been discussed as widely as the disassembly effort in the previous studies (Desai & Mital, 2003) (Shu & Flowers, 1999). While disassembling, various steps must be followed to facilitate the step-by-step removal of all the components. In the case of remanufacturing, further steps beyond disassembly are involved. Assessment of this aspect has not been considered in such detail in the previous studies. In this research, the extended application of the work by Desai & Mital, (2003) is proposed to assess the different steps involved in the product remanufacturing. The scores for all steps can then be aggregated in a similar manner, as proposed for disassemblability (see section 3.3.2), to obtain a value for the actual (E_{RA}), maximum possible ($E_{RMax.}$) and minimum possible effort ($E_{RMin.}$) required during the product remanufacturing. With help of E_{RA}, ERMax and E_{RMin}, a metric to assess the 'E_R' is proposed in Equation (30). By doing so, the current remanufacturing process is evaluated to determine whether it is more physically demanding, or not.

$$\boxed{E_{R} = 1 - \left[\frac{E_{RA} - E_{RMin}}{E_{RMax}' - E_{RMin}}\right]} \tag{34}$$

where,

E_R – Remanufacturing Effort Index

E_{RA} – Actual Effort Score for remanufacturing

$E_{Rmax.}$ – Maximum Effort Score for remanufacturing

$E_{Rmin.}$ – Minimum Effort Score for remanufacturing

Based on the equation in (19), E_R always ranges between 0 to 1, where ‘0’ implies that the remanufacturing process is very physically challenging and ‘1’ means that the process requires the lowest amount of effort by the operator.

4.3.3 *Refurbish Index (RF)*

Refurbishing refers to both the repair of damage to the part and the application of protective/aesthetic coatings (Bras and Hammond, 1996). In the refurbishing stage, one or more components can be refurbished before assembly depending upon the remanufacturing plan. An underlying assumption here is that regardless of the specific process, there will be at the very least a moderate investment of time, energy and/or resources to refurbish a part (Bras and Hammond, 1996). Best case scenario is when there are no components required to be refurbished. That means the remanufacturing of such a product only requires disassembly, cleaning, testing, inspection and lastly, assembly for final acceptance. Bras and Hammond (1996) propose a metric to capture this information which is shown in Equation (31).

$$\boxed{\mu_{Refurbish} = \left(1 - \left(\frac{\mathrm{R}}{\mathrm{N}}\right)\right)} \tag{35}$$

where,

R – number of refurbished components

N – Total number of components

It is proposed that the Equation (31) be borrowed from the work of Bras and Hammond (1996) and used to assess the refurbish score. This metric captures the information in form of a metric where count of refurbished components is compared with the total number of components. This will help in indicating the moderate investment of time, energy and/or resources utilized in the process to enable the refurbishing of that component. The above borrowed metric, gives a score between 0 and 1, where 0 being the least refurbish score and 1 being the highest refurbish score. For sake of consistency in this research work, the notations used to represent refurbish index have been modified to ‘RF’ from ‘$\mu_{Refurbish}$’. Thus, the new form is shown in Equation (32).

$$\boxed{RF = \left(1 - \left(\frac{\mathrm{R}}{\mathrm{N}}\right)\right)} \tag{36}$$

where,

RF – Refurbish Index

4.3.4 *Cleaning Index (CL)*

Cleaning is the process of removing anything which is not intended to be present in the part (Bras and Hammond, 1996). Cleaning activities used on the line to clean various components often requires a major investment from the remanufacturer (Bras and Hammond, 1996). To quantify the cleaning metric, it is necessary to assess the resource requirement for each cleaning process used during the remanufacture of the product (Bras and Hammond, 1996). An example of a prioritization matrix borrowed from the earlier work of Bras and Hammond (1996) is shown in Appendix E. The first step is to determine the activity specific scores. Next, each of the component is assessed for its list of applicable cleaning activities. For example, let ‘2’ and ‘3’ be the activity specific scores for activities ‘d’ and ‘e’ respectively. If both activities are applicable for a component where, activity ‘d’ is required twice and ‘e’ is required thrice. Then the component-actual cleaning score is assessed at ‘13’ (= 2*2 + 3*4). After all the component-actual cleaning scores are assessed, they can be aggregated to obtain product-actual cleaning score. Metric proposed by Bras and Hammond (1996) to rate the cleaning activities is shown in the Equation (33).

$$\boxed{m_{cleaning} = \frac{(\#Ideal)(1)}{(Cleaning\ Score)}} \tag{37}$$

where,

m_{cleaning} – Cleaning rating; #ideal – Theoretical Part Count

Cleaning score - total cleaning score for the product aggregated from the components

Theoretical part count information is not available for all the cases of remanufacturing. Especially, when the remanufacturing company is a 3rd party and not an OEM. Hence to avoid this limitation, it is proposed that the ideal case be established based on expert opinion. As per expert opinion, the least acceptable amount of cleaning activities for each component can be determined. This least case scenario can be used to assess the product-ideal cleaning score. Taking the ratio of product-ideal and product-actual cleaning scores can help shed light on how much the current process deviates from the ideal scenario. The new metric for this thesis is proposed in the Equation (34).

$$\boxed{\mathrm{CL} = \left(\frac{CL_b}{CL_a}\right)} \tag{38}$$

where,

CL – Cleaning Index

CL_b – product-ideal cleaning score; CL_a – product-actual cleaning score

The above proposed metric, gives a score between ‘0’ and ‘1’, where ‘0’ means the remanufacturing process has a high cleaning requirement as per the current process flow and ‘1’ implies the contrary.

4.3.5 *Inspection & Testing Index (IT)*

Testing is process for checking the performance of the product, its sub-assemblies and components against a predefined performance criterion whereas, inspection refers to the process of qualitatively examining parts for damage, usually by visually checking the parts (Bras and Hammond, 1996). Inspection is most often performed during disassembly (for parts which do not require cleaning) or during assembly and refurbish stages immediately after cleaning. To facilitate damage detection visually, the inspection processes generally rely on sets of go-no go gauges and other reference tooling. For some cases of damage detection, given the complexity of the part, advance techniques might be required, *i.e.* Crack detection through magnetic particle inspection. There is a fine line between testing and inspection as testing involves activities which are more complex and generally use more specialized tools and setup. Despite the differences, using simple tools and even specialized or advanced techniques can have an impact on the overall investment. Thus, it makes sense to capture the information related with these activities for quantitative assessment. Bras and Hammond (1996) propose two separate metrics to capture this information for inspection and testing. They are shown in the Equations (35) and (36) respectively.

$$\boxed{m_{inspection} = \frac{(\#Ideal\ Inspections)}{(\#Parts - \#Repl)}} \tag{39}$$

where,

$m_{inspection}$ – inspection score

#ideal inspections – theoretical minimum number of parts

#Parts – Total no. of components; #Repl – Total no. of parts replaced

$$\boxed{m_{testing} = \frac{(\#Test)(10sec)}{(Time_T)}} \tag{40}$$

where,

$m_{testing}$ – testing score

#Test – number of testing activities; $Time_T$ – Total time taken for all the testing

Limitation of Equation (35) is that it considers theoretical part count in its metric. As discussed in earlier sections, this information is not easily available for all the type of manufacturers except for the OEM. Limitation of Equation (36) is that it benchmarks all the testing activity against a standard time of 10 seconds. This can be very misleading as certain testing activities are time based for example, pressure testing, creep testing, etc. Testing activities like this which generally require more than 10 seconds would always achieve low score as per Equation (36). This would lead to a misinformation about so many products that have high but fixed testing time requirement.

Considering the limitations discussed above, a combined metric is proposed for inspection and testing. This metric is similar to Equation (34). An approach like the cleaning score is used in the case of inspection and testing. A prioritization matrix is established to give the activity specific scores based on the share of activity specific investment (See Appendix E). Next, the component specific scores are assessed and then aggregated give the product-actual inspection and testing score (IT_a). For relative comparison, a product-ideal inspection and testing score (IT_b) is established. This score implies that all the components are tested and inspected with the simplest activity applicable on the line. Taking the ratio of IT_a and IT_b, the Inspection & Testing Index (IT) can assessed by the proposed metric shown in Equation (37).

$$\boxed{\mathrm{IT} = \left(\frac{IT_b}{IT_a}\right)} \tag{41}$$

IT – Inspection & testing index

IT_b – product-ideal inspection and testing score

IT_a – product-actual inspection and testing score

The above proposed metric, gives a score between ‘0’ and ‘1’, where ‘0’ means the remanufacturing process has a high inspection and testing requirement as per the current process flow and ‘1’ implies the contrary. Earlier, Figure 13 was presented to show the intended relationship between the proposed metrics and the identified factors. Considering the discussions presented for each of the metrics proposed under the process technology assessment for remanufacturing, it is reasonable to conclude that information from all the intended factors have been used as suggested in Figure 13.

4.4 PHASE III: Incoming Quality Assessment

The time and resources required for the remanufacturing process depend significantly on the incoming quality of the returned product. If the quality is not acceptable, replacement of some components and, in some cases, rejection of the entire product can occur. The importance of this information in context of remanufacturability has not been considered in the previous studies. In this research, phase III attempts to capture this information by proposing a metric for assessing the incoming quality in case of remanufacturability. Figure 17 illustrates an overview of the methodology for the incoming quality assessment.

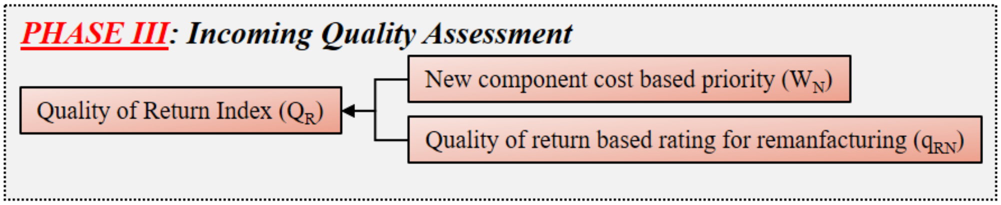


Figure 17 Incoming quality assessment for remanufacturability

Compared to disassemblability, scope of assessment for the incoming quality under remanufacturability is slightly different. For disassemblability, this scope is limited to the point of disassembly (See Figure 3). Whereas, for remanufacturability, this scope extends till the end of the primary inspection stage. Primary inspection is generally conducted to thoroughly check the returned components that have been disassembled and cleaned. It is assumed that all the components with unacceptable quality are identified and separated by the end of this stage. Thus, any failure of components occurring beyond this stage is purely because of the operator or process related setbacks. Hence, the proposed metric is show in Equation (38).

$$\boxed{Q_R = \left(\sum_{1}^{N} q_{RN}\, w_N\right)} \tag{42}$$

where,

Q_R – Quality of return index for remanufacturability

q_{RN} – Binary rating for the N^th component (0 – rejected & replaced, and 1 - accepted) during remanufacturing

Here, the 'c_N' is assessed by the proposed metric shown in the equation (18).

4.5 PHASE IV: Consolidated Index Development

The consolidation of metrics to compute an index with a value between '0' and '1'is presented here. The reasoning behind this has been discussed in section 3.5. Figure 18 gives an overview of the methodology for the Phase IV.

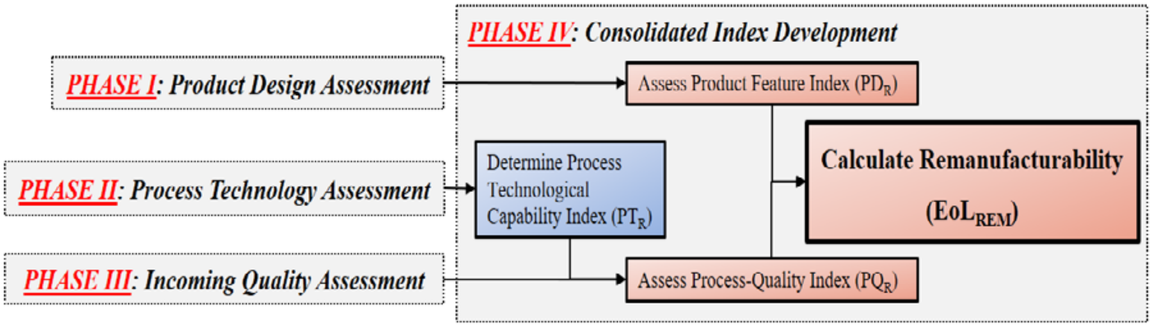


Figure 18 Methodology for Consolidation of Index

Consolidated Index that will be discussed in the upcoming sections are as follows:

5. Product Feature Index for Remanufacturability (PD_R)
6. Process Technological Capability (PT_R)
7. Process-Quality Index for Remanufacturability (PQ_R)
8. Remanufacturability (EoL_R)

4.5.1 *Product Feature Index for Remanufacturability (PD_R)*

'PC_R' and 'PA' metrics described in the sections 4.2.1 and 4.2.2 respectively, can be integrated to provide a single metric to provide an overall assessment of the product design in terms of the ability to remanufacture a product. In this research, a metric is proposed like Equation (20) [see section 3.5.1] for combining PC_R and PA to give a single index. To give equal weightage to PC_R and PA, value of 'α' value is set at 0.5. In this manner both PC_R and PA will carry the same weight (= 0.5). 'PD_R' obtained by integrating PC_R and PA by using the F-measure metric, with 'α' = 0.5, is shown in Equation (39)(20).

$$\boxed{PD_R = \frac{2}{(PC_R)^{-1} + (\mathrm{PA})^{-1}}} \tag{43}$$

4.5.2 *Process Technological Capability for Remanufacturability (PT_R)*

Process Technological Capability for remanufacturability (PT_R) is a proposed metric that integrates the five sub-metrics discussed in section 4.3. These sub-metrics are 'RT', 'E_R', 'RF','CL', and 'IT', respectively. Bras and Hammond (1996) propose a combinatorial metric '$m_{Remanufacturability}$', that attempts to integrate seven process related aspects into a single score. This metric is shown in Equation (21). The use of a modified form of Equation (21) is proposed where the combinatorial metric integrates five instead of seven metrics. The proposed metric for 'PT_R' is shown in Equation (40),

$$\boxed{PT_R = \left(\sum_{l=1}^{5} \frac{w_x}{\mathrm{v}_x}\right)^{-1}} \tag{44}$$

where,

- W_x = Weights based on relative investment such that:

$W_1 = W_{RT}$ for assembly, $W_2 = W_{ER}$ for remanufacturing effort, $W_3 = W_{RF}$ for refurbish, $W_4 = W_{CL}$ for cleaning, and $W_5 = W_{IT}$ for inspection and testing.

- V_x= Scores for different process related aspects such that:

$V_1 = V_{RT}$ for assembly, $V_2 = V_{ER}$ for remanufacturing effort, $V_3 = V_{RF}$ for refurbish, $V_4 = V_{CL}$ for cleaning, and $V_5 = V_{IT}$ for inspection and testing.

The weights are established using a prioritization matrix to determine a relative weighting scheme for all the five sub-metrics. Based on the feedback from the remanufacturers, all the five-process related activities are compared based on the investment involved. The comparison leads to establishment of relative weights with the help of a prioritization matrix. An example of this matrix is shown in the Figure 11. It contains the ratio of all the individual process related investment values. The ratios are populated into the matrix shown in Figure 11 and aggregated horizontally from left to right to establish a process weight. These are then aggregated vertically from top to bottom to give the total weight. 'W_x' can be calculated by taking the ratio of process specific weight to that of the total weight. These are rounded off to two decimal places for convenience.

4.5.3 *Process-Quality Index for Remanufacturability (PQ_R)*

The incoming quality of products (see section 3.5.3) significantly impacts the disassemblability and remanufacturability of a product (Bhattacharya & Kaur, 2015) (Ferguson, 2009). If the incoming quality is unacceptable, then conducting the remanufacturing is futile. Thus, given the QOR, the product or its non-fasteners could be rejected thereby halting the remanufacturing process, even though the process technologically is completely capable. This limitation imposed by the QOR is not addressed explicitly by any metric in the previous studies. In this research, to represent the limitation imposed by QOR on 'PT_R', a metric 'PQ_R' is proposed and shown in Equation (41).

$$\boxed{PQ_R = PT_R * Q_R} \tag{45}$$

where,

PQ_R – Process-Quality Index for remanufacturability

'PT_R' always returns a value between '0' and '1', where '0' means highest limitation on product remanufacturability due to QOR. And '1' implies highest product remanufacturability due to best incoming QOR.

4.5.4 *Remanufacturability (EoL_{REM})*

As discussed earlier, remanufacturability is enabled by various factors and metrics (see sections 4.1 to 4.4). All the factors considered from the aspects of product design, process technology and incoming quality in this research work, have not been considered before. That is why this quantitative methodology is unique than the previous studies. The scores from sections 4.5.1 and 4.5.3 are integrated in a similar manner as proposed in section 3.5.4. Hence, the combinatorial metric based on Equation (24) is proposed to integrate the scores of 'PQ_R' and 'PD_R' metrics into a single value of 'EOL_{REM}'. The proposed metric 'EOL_{REM}' is shown in Equation (42). 'α' in this case is again set at 0.5 so that both 'PQ_R' and 'PD_R' get equal weights.

$$\boxed{EoL_{REM} = \frac{2}{(PD_R)^{-1} + (PQ_R)^{-1}}} \tag{46}$$

where,

EoL_{REM} – Remanufacturability

4.5.5 *Analytical model for EoL$_{REM}$*

Analytical model in this research work is defined as the model that addresses the interaction of all factors discussed in Chapter 4. Using the proposed methodology, to assess the EoL$_{REM}$ can be further simplified and expressed in the form underlying sub-metrics. Doing so, makes it easier for the user to apply the above methodology in a more succinct manner. The simplified version of Equation (46) will be obtained by substituting Equations (43), (44), and (45) in a step by step approach.

Step 1: Substituting Equation (43) in Equation (46), we get,

$$\boxed{EoL_{REM} = \frac{2 * Q_R PT_R PD_R}{Q_R PT_R + PD_R}} \tag{47}$$

Step 2: Like Equation (28), by doing further substitution and simplification of Equation (47), we get the final form of the leading function for Remanufacturability (EoL$_{REM}$). This is shown in Equation (48):

$$\boxed{\begin{aligned} EoL_{REM} = {} & [\Big(0.25 * (PA^{-1} + PC_R^{-1})\Big) + (0.5 * Q_R^{-1} \\ & * (W_{RT}RT^{-1} + W_{RF}RF^{-1} + W_{ER}E_R^{-1} + W_{CL}CL^{-1} + W_{IT}IT^{-1})]^{-1} \end{aligned}} \tag{48}$$

Chapter 5 Case Study: Data Collection

5.1 Background

To demonstrate the application of the proposed methodology in chapters 3 and 4, a case study partner is selected based in Lexington, Kentucky. SRC of Lexington specializes in the remanufacture of large engines, hydraulics and power train components for a wide range of OEMs. Being a 3rd party remanufacturer, SRC provides for a unique scenario where the rejected cores with no salvageable value are scrapped to a recycling dealer. The proposed method is used to assess the disassemblability and remanufacturability of two different products. Products with high volume were selected as they present sufficient opportunity for data recording in a feasible amount of time. The selected products are known as A and B series respectively.

5.2 Bill-of-Material (BOM)

The BOM for both the product types, established based on information from SRC, are shown in Table 6 and Table 7, for Series A and Series B, respectively. The BOM also contains the following information populated from both feedback and on-the-floor observations:

1. Default Rejection as per OEM? (Yes/No)
2. Component type classification [‘f’ (category 1) or ‘nf’]
3. Fastener category classification (Category1/2/3)
4. Cleaned Component? (Yes/No)
5. Tested Component? (Yes/No)
6. Inspected Component? (Yes/No)
7. Component Cost based weight. (c_N)
8. Component Cost based weight [over total inspected BOM during disassembly]. (w_l)
9. Component Cost based weight [over total inspected BOM during remanufacturing]. (w_u)

Table 6 BOM and Relevant classification information for Series A

Sno.	Material Description	Qty	Default Reject?	f / nf	Categ. (1/2/3)	Cleaning requirement	Testing requirement	Inspecting requirement	Weight (c_N)	Weight (W_l)	Weight (W_u)
1	Series A Head	1	No	nf	-	Yes	Yes	Yes	0.69	1	0.81
2	Intake Valve Sleeve	2	Yes	nf	-	N/A	N/A	N/A	0.02	-	0.005
3	Intake Valve Seal	2	Yes	nf	-	N/A	N/A	N/A	0.00	-	-
4	Exhaust Valve Seal	2	Yes	nf	-	N/A	N/A	N/A	0.00	-	-
5	Intake Valve	2	Yes	nf	-	N/A	N/A	N/A	0.08	-	-
6	Exhaust Valve	2	Yes	nf	-	N/A	N/A	N/A	0.14	-	-
7	Keeper	8	Yes	nf	3	N/A	N/A	N/A	0.00	-	-
8	Inner Exhaust Spring	2	Yes	nf	-	N/A	N/A	N/A	0.00	-	-
9	Outer Exhaust Spring	2	Yes	nf	-	N/A	N/A	N/A	0.00	-	-
10	Inner Intake Spring	2	Yes	nf	-	N/A	N/A	N/A	0.00	-	-
11	Outer Intake Spring	2	Yes	nf	-	N/A	N/A	N/A	0.00	-	-
12	Hex Plug	1	No	f	1	Yes	N/A	N/A	0.00	-	-
13	Exhaust Valve Sleeve	2	Yes	nf	-	N/A	N/A	Yes	0.02	-	0.005
14	Valve Seat	4	Yes	nf	2	N/A	N/A	Yes	0.03	-	0.18
15	Washer	8	No	nf	-	Yes	N/A	N/A	0.00	-	-
16	Retainer	4	No	nf	-	Yes	N/A	N/A	0.01	-	-

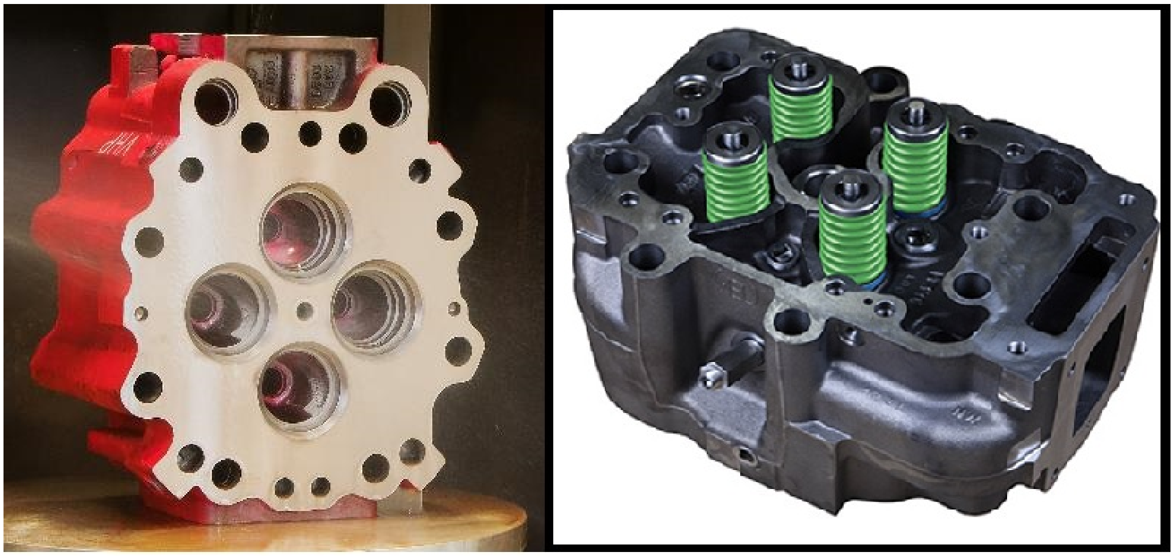
Table 7 BOM and Relevant classification information for Series B

Sno.	Material Description	Qty	Default Reject?	f / nf	Categ. (1/2/3)	Cleaning requirement	Testing requirement	Inspecting requirement	Weight (c_N)	Weight (W_l)	Weight (W_u)
1	Series B head	1	No	nf	-	Yes	Yes	Yes	0.61	0.69	0.56
2	Intake Valve Sleeve	2	Yes	nf	-	N/A	N/A	N/A	0.01	-	-
3	Exhaust Valve Sleeve	2	Yes	nf	-	N/A	N/A	N/A	0.01	-	-
4	O-ring	2	Yes	nf	-	N/A	N/A	N/A	0.00	-	-
5	Keeper	8	Yes	nf	3	N/A	N/A	N/A	0.00	-	-
6	Exhaust Valve	2	Yes	nf	-	N/A	N/A	N/A	0.08	-	-
7	Intake Valve	2	Yes	nf	-	N/A	N/A	N/A	0.05	-	-
8	Exhaust Valve Seal	2	Yes	nf	-	N/A	N/A	N/A	0.00	-	-
9	Intake Valve Seal	2	Yes	nf	-	N/A	N/A	N/A	0.00	-	-
10	Inner Intake Spring	2	Yes	nf	-	N/A	N/A	N/A	0.00	-	-
11	Inner Exhaust Spring	2	Yes	nf	-	N/A	N/A	N/A	0.00	-	-
12	Outer Intake Spring	2	Yes	nf	-	N/A	N/A	N/A	0.00	-	-
13	Outer Exhaust Spring	2	Yes	nf	-	N/A	N/A	N/A	0.00	-	-
14	Spark Plug Sleeve	1	No	nf	-	Yes	N/A	Yes	0.13	0.28	0.22
15	Spark Plug Seal	1	No	nf	-	Yes	N/A	N/A	0.00	-	-
16	Spark Plug Flange	1	No	nf	-	Yes	N/A	Yes	0.01	0.03	0.02
17	Washer	8	No	nf	-	Yes	N/A	N/A	0.00	-	-
18	Retainer	4	No	nf	-	Yes	N/A	N/A	0.01	-	-
19	Hex Nut	2	No	f	1	Yes	N/A	Yes	0.00	-	-
20	Valve Intake Seat	2	Yes	nf	2	N/A	N/A	Yes	0.02	-	0.05
21	Valve Exhaust Seat	2	Yes	nf	2	N/A	N/A	Yes	0.04	-	0.15

5.3 Case Study Product Details

Additional details about Series A and Series B products chosen for the case study are discussed in the sections below.

5.3.1 *Series A Process Layout*



Front Side

Rear Side

Figure 19 Series A - Head front and rear appearance (SRC, 2017)

The remanufacturing and disassembling process on the floor slightly differs for Series A when compared to Series B. From the company's perspective, the remanufacturing of both the cylinder head takes place in 2 stages. The first stage consists of processes like disassembly, inspection and major cleaning activities. On the other hand, the second stage includes processes like assembly, refurbishing, minor cleaning and major inspection and testing activities. Series A product's process flow diagram developed from on-the-floor observation is shown in Figure 21 and Figure 22, for Stage 1 and Stage 2, respectively.

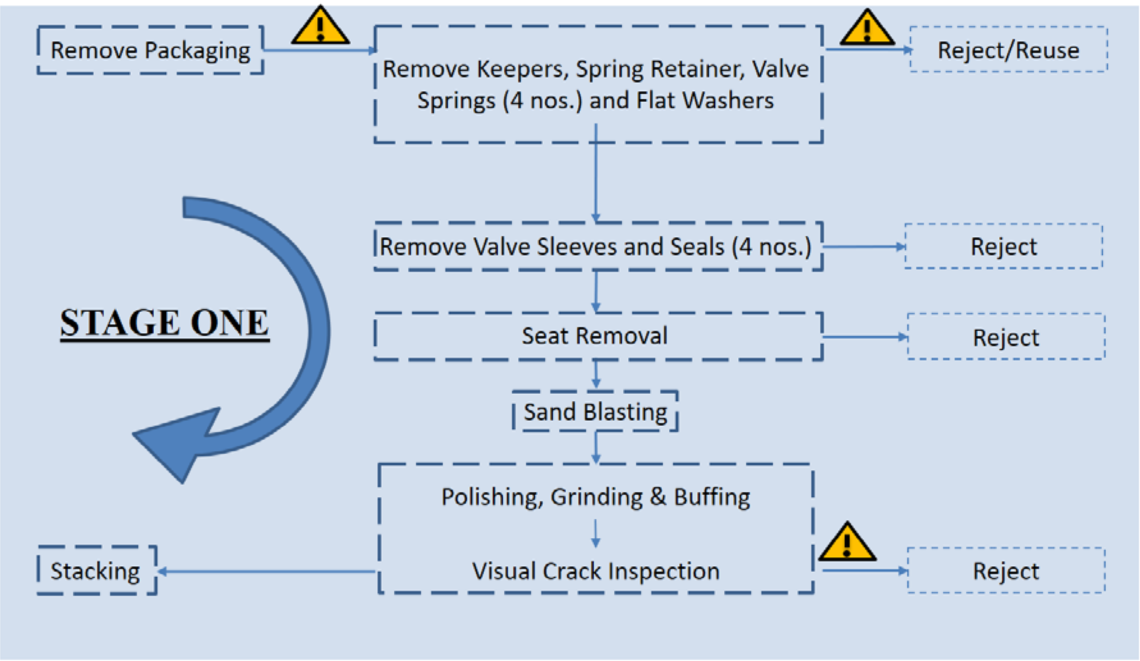


Figure 20 Stage One sequence for Series A.

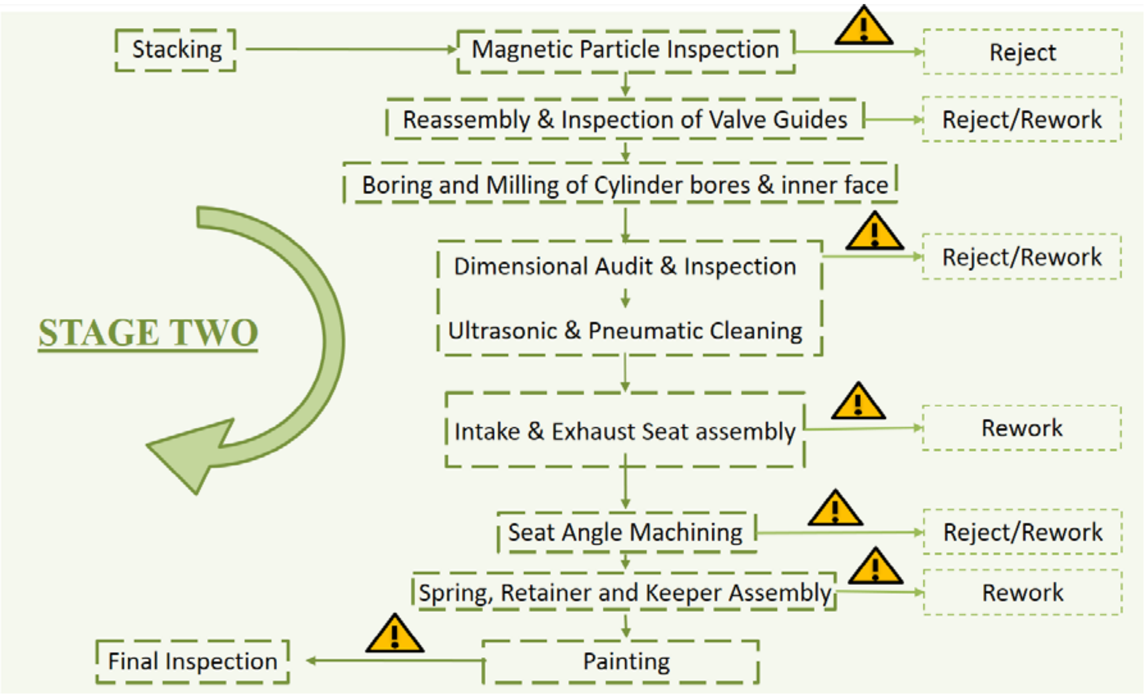
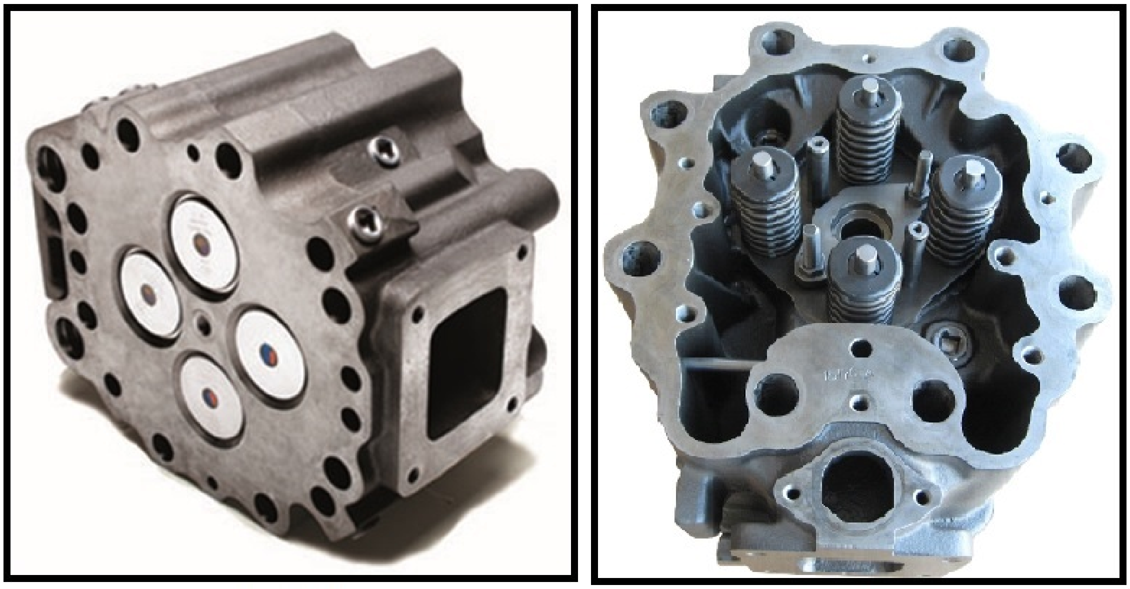


Figure 21 Stage Two sequence for Series A.

5.3.2 *Series B Process Layout*



Front Side

Rear Side

Figure 22 Series B - Head front and rear appearance (SRC, 2017)

Series B is a latest generation whereas Series A is the older generation of the same product. Series B product's process flow diagram developed from on-the-floor observation is shown in Figure 24 and Figure 25. The Triangle Markers represent the quality decision points in the different stages of breakdown and build up. Series B has several different steps which have been highlighted in red and shown in Figure 24 and Figure 25, for Stage 1 and Stage 2, respectively.

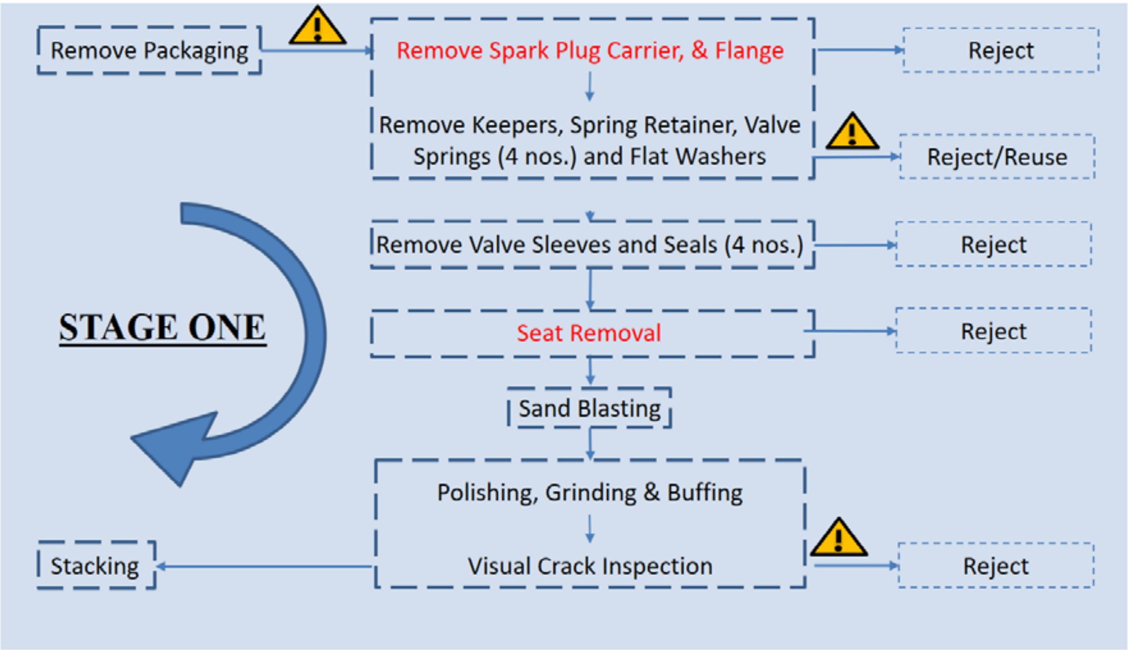


Figure 23 Stage One sequence for Series B

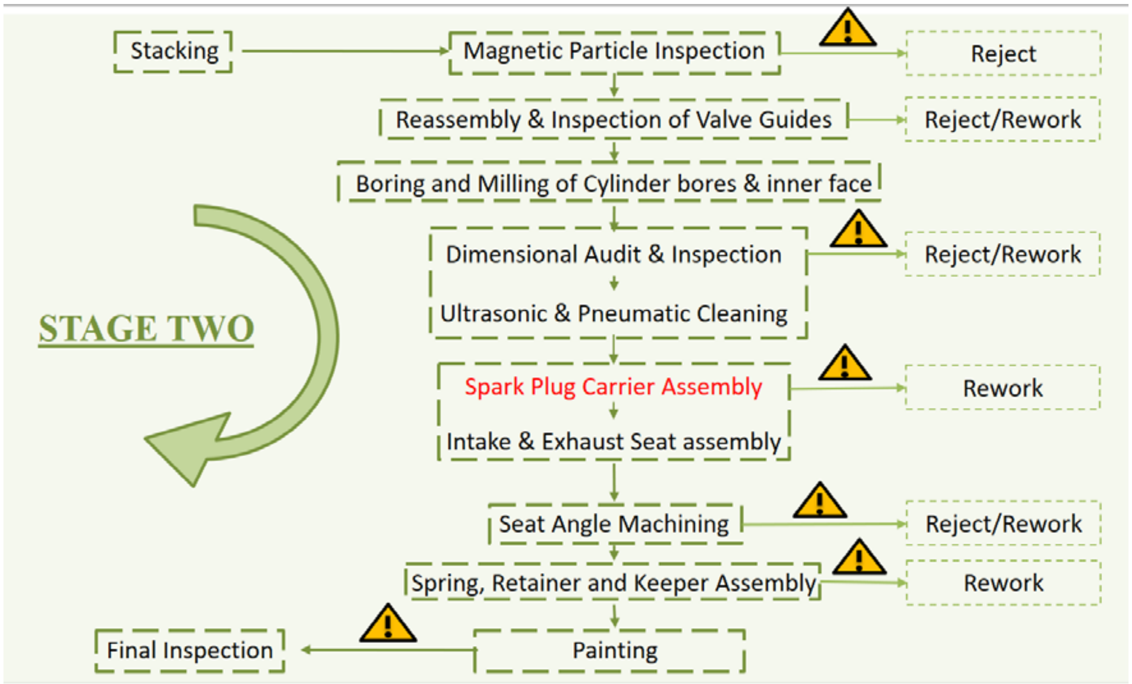


Figure 24 Stage Two sequence for Series B.

5.4 Process-related Investments

This section establishes the prioritization matrix based on the value invested in disassembly and remanufacturing processes, respectively. The investments costs are used to establish the relative weight for ‘CL’, ‘PT_D’, ‘PT_R’ and, ‘IT’. Cost of various process technologies based on feedback from SRC, are shown in Table 8.

Sno.	Process/Facilities	Total Value	Investment
1	**Cleaning Process**	**$ 105,000.00**	
1.1	Oil Bath		$ 60,000.00
1.2	Sand Blasting		$ 30,000.00
1.3	Buffing/Grinding		$ 10,000.00
1.4	Hot Tank cleaning/Ultrasonic wash		$ 5,000.00
2	**Refurbish Process**	**$ 210,000.00**	
2.1	CNC Machine		$ 90,000.00
2.2	Rottler Machine		$ 120,000.00
3	**Assembly Process**	**$ 15,000.00**	
3.1	Press Station 1		$ 5,000.00
3.2	Press Station 2		$ 5,000.00
3.3	Tooling		$ 5,000.00
4	**Disassembly Process**	**$ 25,000.00**	
4.1	Press Station 1		$ 5,000.00
4.2	Press Station 2		$ 5,000.00
4.3	Tooling		$ 5,000.00
4.4	Heat Flux Gun		$ 10,000.00
5	**Inspection & Testing Process**	**$ 22,000.00**	
5.1	Tooling		$ 3,000.00
5.2	Magnetic Particle Inspection		$ 15,000.00
5.3	Pressure Testing		$ 3,000.00
6	**Manpower Training**	**$ 2,500.00**	
6.1	Training Time + Weekly labor		$ 2,500.00

Table 8 Process Investments (SRC, 2017)

As per the investment details listed in Table 8, the prioritization matrix is established for the process related aspects of disassembly, as shown in Table 9.

Table 9 Prioritization Matrix for Disassemblability (Weights of ‘PT_D’).

‘PT_D’ weights	Disassembly	Disassembly Effort	Total	Weights
Disassembly	1	11	12	**0.92**
Disassembly Effort	0.1	1	1.1	**0.08**
			12.1	

Similarly, the prioritization matrix is established for process related aspects, for remanufacturing, as shown in Table 10.

Table 10 Prioritization Matrix for Remanufacturability (Weights of 'PT_R').

Aspect	RT	RF	CL	IT	E_R	Weights	Weights %
RT	1.0	1.2	2.4	11.5	101.0	117.1	0.427
RF	0.8	1.0	2.0	9.5	84.0	97.38	0.355
CL	0.4	0.5	1.0	4.8	42.0	48.69	0.177
IT	0.1	0.1	0.2	1.0	8.8	10.20	0.037
E_R	0.0	0.0	0.0	0.1	1.0	1.16	0.004
						274.5	

The prioritization matrix setup to determine scores for the different types of cleaning activities used during product remanufacturing, also based on information in Table 8, is shown in Table 11.

Table 11 Prioritization matrix for establishing scores for each type of cleaning process.

Cleaning process			A	B	C	D	E	Total Weight	Weight %	Score
1	Buff, grind, polish, blow	A	1	0.33	0.2	0.14	0.11	1.8	3%	**1**
2	Jet (water/air) cleaning	B	3	1	0.33	0.2	0.14	4.7	8%	**3**
3	Ultrasonic cleaning	C	5	3	1	0.33	0.2	9.5	17%	**6**
4	Sand Blasting	D	7	5	3	1	0.33	16.3	28%	**9**
5	Hot tank soap wash	E	9	7	5	3	1	25.0	44%	**15**
								57.3	100%	33

The prioritization matrix setup to determine scores for the different types of inspection and testing activities used during product remanufacturing, also based on information in Table 8, is shown in Table 12.

Table 12 Inspection and Testing Prioritization Matrix based on investment

Inspection &Testing Prioritization Matrix		A	B	C	Total Weight	Weight %	Score
MPT	A	1	5	5	11	71%	**5.00**
Tool	B	0.2	1	1	2.2	14%	**1.00**
PT	C	0.2	1	1	2.2	14%	**1.00**
					15.4		

The prioritization matrix established in Table 9, Table 10, Table 11, and Table 12 will aid the case study assessment discussed in Chapter 6.

5.5 Time Study and Quality of Returns

As part of the observation, a time study was conducted for the remanufacturing of Series A and Series B cylinder heads. The time taken for a core to move through both stages of remanufacturing was recorded. For a healthy data set, 30 recordings for each of the product type were taken. This data for Series A and Series B is shown in Appendix I and Appendix J respectively. The cores highlighted with red font in these Appendix are the ones that got scrapped during remanufacturing for various reasons. Grading for the quality of returns during disassembly and remanufacturing (‘q_{RN}’ & ‘q_{DN}’) has been allotted individually for 30 cores under both the product types. This grading data is shown in the Appendix K and Appendix L. The tables found in these Appendices will be used to compute the Quality Index (Q_D & Q_R) for both product types.

5.6 Single Quality Gate vs Multi Quality Gates

Prior to the commencement of this case study, it was believed that the general scheme of quality acceptance for an incoming core involved only a single binary (yes/no) decision point. The schematic for a single binary decision point or a single quality gate, that was assumed prior to the case study, is shown in Figure 26.

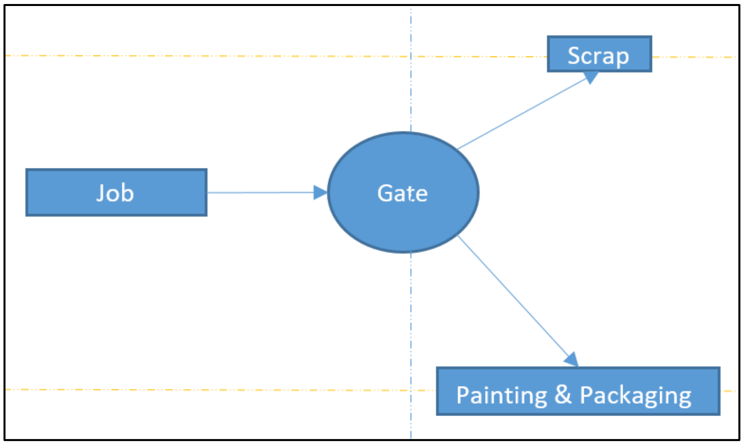


Figure 25 Presumed Single Quality Gate Scheme.

After the completion of case study, it was found that the remanufacturing process for both the product types involved, not a single, but, multiple points of quality acceptance/decision gates. Also, not all of them were binary. A total of seven quality decision gates were identified for both the product types. As per observations and expert opinion, time taken by the core to travel between gates, and probability of pass/rework/scrap, were determined for both the product types. The details are shown in Table 13 and Table 14 for Series A and Series B respectively.

Table 13 Series A related information.

Position	Quality Gate	Time Taken (minutes)		Pass Rate	Rework Rate	Scrap Rate
		To reach	Between			
S1	G1	**4**		**0.85**	**-**	**0.15**
S2	G2	**34**	**30**	**0.97**	**-**	**0.03**
S3	G3	**37**	**3**	**0.92**	**-**	**0.08**
R1	G4	**41**	**4**	**0.99**	**0.01**	**-**
R2	G5	**71**	**30**	**0.8**	**0.15**	**0.05**
R3	G6	**81**	**10**	**0.99**	**0.01**	**-**
R4	G7	**92**	**11**	**0.98**	**0.02**	**0.01**

Table 14 Series B related information.

Position	Quality Gate	Time Taken (minutes)		Pass Rate	Rework Rate	Scrap Rate
		To Reach	Between			
S1	G1	**4**	**-**	**0.85**	**-**	**0.15**
S2	G2	**49**	**45**	**0.85**	**-**	**0.15**
S3	G3	**54**	**5**	**0.99**	**-**	**0.01**
R1	G4	**69**	**15**	**0.99**	**0.01**	**-**
R2	G5	**94**	**25**	**0.88**	**0.06**	**0.06**
R3	G6	**139**	**45**	**0.99**	**0.01**	**-**
R4	G7	**164**	**25**	**0.87**	**0.12**	**0.01**

Seven quality decision gates observed as identified as: G1, G2, G3, G4, G5, G6 and G7. Depending upon whether the core is scrapped/refurbished, the gate positions are labelled as: S1, S2, S3, R1, R2, R3, R4 respectively. The positions represent Scrap stage 1, 2, and 3 for S1, S2, and S3, respectively. And Refurbish Stage 1, 2, 3 and 4 for R1, R2, R3, and R4, respectively. The scrap stages S1, S2 and S3 are binary decision points, where the core is either scrapped or not. Similarly, R1 and R3 are also binary decision points, where the core undergoes rework or passes without rework. However, R2 and R4 are ternary decision points, where the core can either pass without rework (or) undergo rework and then pass (or) get scrapped. The remanufacturing flow ends when a core gets scrapped. The loss of time invested in the form of labor and, loss of cost invested in form of new components, if any, are all borne by SRC. It was found that the average operation's cost at SRC is $72/hour or $1.2/min. This implies that it takes $1.2/min to maintain the regular operations for Series A and Series B product types with respect to consumables, operator labor rate, training, etc. Given the rate of $1.2/min and average times for core rework and core movement from gate to gate, a costing scheme was developed for all the rework and scrap decisions which is shown in Table 15, and Table 16.

As per the discussion with SRC, one of the biggest issue was reduced visibility of the cost implications due to on-line scrap and/or rework cases for both the product types. The management understands that the scrapping of cores early in the process had less cost implications but were unclear about the ones which got scrapped very late in the process.

Table 15 Rework Time & Cost - Series A & B

	Series A		Series B	
Position	Average Rework (min)	Total Cost	Average Rework (min)	Cost
R1	5	$ 3.00	5	$ 6.00
R2	10	$ 6.00	10	$ 12.00
R3	10	$ 6.00	10	$ 12.00
R4	5	$ 3.00	5	$ 6.00

Table 16 Scrap Cost - Series A & B

	Scrap Cost	
Position	Series A	Series B
S1	$ 4.80	$ 4.80
S2	$ 40.80	$ 58.80
S3	$ 44.40	$ 64.80
R2	$ 85.20	$ 112.80
R4	$ 103.20	$ 172.80

Using the data collected in Table 13 and Table 16, a study was conducted to develop a probability tree which would consist of all the possible outcomes with their respective probability of occurrence (POC) and cost (CI). The probability Tree for Series A and Series B can be found in Appendix F, and Appendix G respectively. A total of 29 outcomes for both the product types were determined along with their respective POC and CI. The details are shown in Table 17 and Table 18 for Series A and B, respectively. From these tables, it can be determined that outcomes 1 to 3, 10, 13 and 21 to 28 are the most unfavorable, because, they are all loss-making. Outcome 4 is the most profitable. Outcome 29 has the most rework cost. It is also observed that the amount of loss increases for the scrapped cores occurring later in the system or at the later gates. This confirms the initial understanding presented by the management that identifying the defective cores earlier in the system incurres lesser losses and hence, investments should be made to reduce the unfavorable outcomes that are currently identified later in the remanufacturing process (*i.e.* S3, R2 & R4). For Series A and B respectively, outcome specific POC and CI, determined from the feedback and observations, will aid SRC in their future planning and thereby, eventually improve the POC for selected favorable outcomes for both the product types.

Table 17 List of outcomes and costs - Series A

Outcome	POC	Net Gain	Comments
1	15.00%	$ (4.80)	Scrap at S1
2	2.55%	$ (58.80)	Scrap at S2
3	6.87%	$ (64.80)	Scrap at S3
4	58.07%	$ 24.00	No Rework
5	1.19%	$ 21.00	Rework at R4
6	0.59%	$ 18.00	Rework at R3
7	0.01%	$ 15.00	Rework at R3, & R4
8	10.89%	$ 18.00	Rework at R2
9	0.22%	$ 15.00	Rework at R2, & R4
10	3.74%	$ (85.20)	Scrap at R2
11	0.11%	$ 12.00	Rework at R2, & R4
12	0.00%	$ 9.00	Rework at R2, & R4
13	0.04%	$ (88.00)	Scrap at R2
14	0.59%	$ 21.00	Rework at R1
15	0.01%	$ 18.00	Rework at R1, & R4
16	0.01%	$ 15.00	Rework at R1, & R3
17	0.00%	$ 12.00	Rework at R1, R3, & R4
18	0.11%	$ 15.00	Rework at R1, & R2
19	0.00%	$ 12.00	Rework at R1, R2, & R4
20	0.00%	$ 9.00	Rework at R1, R2, & R3
21	0.59%	$(135.00)	Scrap at R4
22	0.01%	$(138.00)	Scrap at R4
23	0.11%	$(141.00)	Scrap at R4
24	0.00%	$(144.00)	Scrap at R4
25	0.01%	$(138.00)	Scrap at R4
26	0.00%	$(141.00)	Scrap at R4
27	0.00%	$(144.00)	Scrap at R4
28	0.00%	$(147.00)	Scrap at R4
29	0.00%	$ 6.00	Rework at R1, R2, R3, & R4

Table 18 List of outcomes and costs - Series B

Outcome	POC	Net Gain	Comments
1	15.00%	$ (4.80)	Scrap at S1
2	12.75%	$ (58.80)	Scrap at S2
3	0.72%	$ (64.80)	Scrap at S3
4	53.67%	$ 135.00	No Rework
5	7.40%	$ 129.00	Rework at R4
6	0.54%	$ 123.00	Rework at R3
7	0.07%	$ 117.00	Rework at R3, & R4
8	3.66%	$ 123.00	Rework at R2
9	0.50%	$ 117.00	Rework at R2, & R4
10	4.25%	$ (112.80)	Scrap at R2
11	0.04%	$ 111.00	Rework at R2, & R4
12	0.01%	$ 105.00	Rework at R2, & R4
13	0.04%	$ (124.80)	Scrap at R2
14	0.54%	$ 29.00	Rework at R1
15	0.07%	$ 123.00	Rework at R1, & R4
16	0.01%	$ 117.00	Rework at R1, & R3
17	0.00%	$ 111.00	Rework at R1, R3, & R4
18	0.04%	$ 117.00	Rework at R1, & R2
19	0.01%	$ 111.00	Rework at R1, R2, & R4
20	0.00%	$ 105.00	Rework at R1, R2, & R3
21	0.62%	$ (246.00)	Scrap at R4
22	0.01%	$ (258.00)	Scrap at R4
23	0.33%	$ (258.00)	Scrap at R4
24	0.00%	$ (270.00)	Scrap at R4
25	0.04%	$ (252.00)	Scrap at R4
26	0.00%	$ (264.00)	Scrap at R4
27	0.00%	$ (264.00)	Scrap at R4
28	0.00%	$ (276.00)	Scrap at R4
29	0.00%	$ 99.00	Rework at R1, R2, R3, & R4

Chapter 6 Case Study: Application

6.1 Disassemblability Assessment

Methodology for both 'ilities' has been discussed in Chapter 3 and 4 respectively. Accordingly, a step-by-step assessment of design, quality and process related aspects will follow in this chapter. Chapter 5 presents the information recorded through on-the-floor observations and derived from expert opinion at SRC (*i.e.* crew, upper management and engineering division familiar with both the product types). This information will be used in section 6.1 and 6.2 to exercise relevant metrics as per the methodology.

6.1.1 *PHASE I: Product Design Assessment*

6.1.1.1 Product Complexity for Disassemblability (PC_D)

Initial step of the methodology is to assess the product complexity of the product. 'PC_D' builds upon the fastener complexity (F_C) and non-fastener complexity during disassembly (ND_C). This requires the identification of all the non-fasteners (nf), fasteners (Category 1/2/3), and number of fastener for each type (f_i) from the BOM. This information can be found in Table 6 and Table 7 for Series A and Series B respectively. Post identification of fasteners, using Appendix I, the values of 'i', 'j' and 'k' for different fasteners is obtained. Using Equations (2), (3) and (4), the values for 'F_A', 'F_I', and 'F_C' are assessed, respectively. As per the discussion presented in Section 3.2.1, category 3 fasteners are not considered when calculating '$\sum f_i$'. The results for 'F_A', 'F_I', and 'F_C' for both the product types can be found in Table 19 and Table 20 respectively.

Table 19 Fastener Complexity Assessment table for Series A

i	Component	j	k	f_i	$Log_2(f_i+1)$	Complexity
1	Hex Plug	1	2.1	1	1	2.1
2	Valve Seat	2	1.8	4	2.32	8.35
3	Keeper	3	0	8	3.17	0
F_A						10.45

	Min.(j)	Min.(k)	$\sum f_i$	$Log_2(\sum f_i+1)$	Complexity
F_I	1	2.1	5	2.58	5.42
		F_C			**0.52**

Table 20 Fastener Complexity Assessment table for Series B

i	Component	j	k	f_i	$Log_2(f_i+1)$	Complexity
1	Hex Plug	1	2.1	2	1.58	3.32
2	Valve Seat	2	1.8	4	2.32	8.35
3	Keeper	3	0	8	3.17	0
F_A						11.67

	Min.(j)	Min.(k)	$\sum f_i$	$Log_2(\sum f_i+1)$	Complexity
F_I	1	2.1	6	2.81	**5.9**
		F_C			**0.51**

Series A and B were assessed to have very similar Fastener Complexity rating of 0.52 and 0.51 respectively. Number of fastener for Series B is greater compared to Series A. Thus, Series B has a lower score.

The next step is to assess the non-fastener complexity that arises due to quick inspections of critical components during disassembly. As per observation, only one such critical component for Series A and B was found that was prone to a quick inspection. The information for ‘l’ and ‘W_l’ can be found in Table 6 and Table 7 respectively. The details for ‘I_l’, ‘T_l’, and ‘ND_C’ are presented in Table 21 and Table 22.

Table 21 Non-fastener Complexity Assessment for Series A

S.no	Part	Qty	I_l	T_l	W_l	nf_l
1	Cylinder head	1	1	6	1.00	0.83
					ND_C	**0.83**

Table 22 Non-fastener Complexity Assessment for Series B

S.no	Part	Qty	I_l	T_l	W_l	nf_l
1	Cylinder head	1	1	9	1.00	0.89
					ND_C	**0.89**

The number of inspected features on both the product types is one. But having different geometry for the head is causing the number of available features for inspection to vary for both the product types. Due to which, Series B having a more complex geometry is assessed to have a lower non-fastener complexity despite having the same number of inspected features as compared to Series

A. This assessment makes sense, as the more geometrically complex product type is rated better given only 1 feature is inspected.

Next step is to determine the weights to derive PC_D from F_C and ND_C for both the product types. ‘N’ for Series A and B are 42 and 47 respectively. ‘f’ observed for Series A and B was 1 and 2 respectively. Hence, ‘nf’ for A and B was determined at 41 and 45 respectively. Hence, the assessments for z_1, z_2, and PC_D are shown in Table 23.

Table 23 Product Complexity for Disassemblability for Series A and Series B

	Series A	Series B
ND_C	0.83	0.89
F_C	0.52	0.51
Z_1	0.98	0.96
Z_2	0.02	0.04
PC_D	0.82	0.87

6.1.1.2 Disassembly Product Accessibility (PA)

Product accessibility can be assessed from the Equation (11), (12), and (13). Accessibility is measured in the same manner for all the components using Equation (11). Post accessibility assessment, individual adjusted component scores are established from Equation (12). Then the overall PA is assessed using Equation (13). Accessibility calculations and dimensional data for each component can be found in Table 61 and Table 62 for Series A and B respectively (See Appendix H). ‘PA’ for Series A and Series B were assessed to be 0.87 and 0.90 respectively.

6.1.2 *PHASE II: Process Technology Assessment*

6.1.2.1 Disassembly Score (D)

‘D’ is assessed with the help of Equation (15). Before that, an interesting approach was adapted to determine the actual times for disassembly in the case of both the product types. Time Study for A and B (See Appendix I and Appendix J) has already been recorded to give the actual disassembly times for each core under each product type. Taking an average for all the cores under each product type was initial conceived as way of reflecting the overall batch actual time. Due to variation in time, it was determined that taking an average can be misleading and hence, regression analysis was conducted between the ‘q_{DN}’ and the actual core specific disassembly times. The result for the regression analysis are shown in Equations (43) and (44). Data from ‘q_{DN}’ for each core is showed in the upcoming section 6.1.3 for consistency. The results for Series A and B are shown in Table 24.

$$Time_{D\ for\ Series\ A} = -93.14 * Q + 76.94 \quad (49)$$

$$Time_{D\ for\ Series\ B} = -6.03 * Q + 15.80 \quad (50)$$

Table 24 ‘D’ Scores for Series A and Series B

	T_D (min)	T_{PD} (min)	**D**
Series A	11.7	9	**0.70**
Series B	11.3	9.5	**0.81**

6.1.2.2 Disassembly Effort Index (E_D)

To assess the Disassembly Effort Rating for Disassembly (E_D) of Series A and Series B, Appendix M, Appendix N and Equation (16) are utilized. Disassembly process is scored based on the Appendix D scoring scheme. The actual, maximum and minimum case scores for Series A and Series B are substituted in Equation (16) for calculation of ‘E_D’. Results obtained are shown in the Table 25 for Series A and Series B respectively.

Table 25 ‘E_D' results for both product types

Effort	**Series A**	**Series B**
E_{DA}	421.5	462
E_{DMin}	307.3	345.3
E_{DMax}	962.5	1084.5
E_D	**0.83**	**0.84**

6.1.3 *PHASE III: Incoming Quality Assessment*

The quality of returns for both the products is established in 3 steps. 1st step is to determine the cost based weight for each component (c_N). To calculate the weights for each component Equation (18) is used. This has already been computed and shown in the Table 6 and Table 7 for Series A and B respectively. The next step is to gather the data for individual cores by establishing quality grading information (q_{DN}). In this case study, 'q_{DN}' for each product type is recorded by tracking 30 individual cores on the floor shop. The 'q_{DN}' ratings for each component of all the 30 cores can be found in the Appendix K. Incoming Quality can be assessed using the Equations (17). Results are shown in Table 26. 'Q_D' is assessed for each individual core and then averaged for all the cores to give a batch level 'Q_D'.

Table 26 Core wise and Batch wise 'Q_D' results for Series A and B.

Order/Core	Order Specific 'Q_D'		Order/Core	Order Specific 'Q_D'	
	Series A	Series B		Series A	Series B
1	0.70	0.76	16	0.69	0.75
2	0.70	0.76	17	0.69	0.63
3	0.70	0.76	18	0.69	0.76
4	0.70	0.76	19	0.70	0.76
5	0.70	0.76	20	0.70	0.76
6	0.69	0.76	21	0.70	0.76
7	0.69	0.76	22	0.70	0.76
8	0.70	0.76	23	0.70	0.76
9	0.70	0.76	24	0.70	0.76
10	0.70	0.76	25	0.70	0.76
11	0.70	0.76	26	0.70	0.75
12	0.70	0.75	27	0.70	0.76
13	0.70	0.63	28	0.70	0.75
14	0.70	0.76	29	0.70	0.76
15	0.70	0.75	30	0.70	0.76
Batch Average 'Q'				**0.70**	**0.75**

6.1.4 *PHASE IV: Consolidated Index Development*

6.1.4.1 Product Feature Index for Disassemblablity (PD_D)

PD_D is assessed by using Equation (20). The assessment for both the products are as shown in Table 27.

Table 27 'PD_D' results for both the product types

	Series A	Series B
PA	0.87	0.90
PC_D	0.82	0.87
PD_D	**0.84**	**0.88**

As per the assessment, Series B as a better product feature index compared to Series A.

6.1.4.2 Process Technological Capability for Disassemblability (PT_D)

'PT_D' is assessed by combining the 'D' and 'E_D' scores with the help of Equation (22). 'PT_D' assessments for Series A and Series B are shown in Table 28 and Table 29 respectively.

Table 28 Series A - 'PT_D' assessment

	Scores	Weight
E_D	0.83	0.08
D	0.70	0.92
PT_D	0.71	

Table 29 Series B - 'PT_D' assessment

	Scores	Weight
E_D	0.84	0.08
D	0.81	0.92
PT_D	0.81	

The weights for **D** and **E_D** scores have been obtained from Table 9 for both the products. Since the facilities used are the same of both the products, the weights used are also the same.

6.1.4.3 Process-Quality Index for Disassemblability (PQ_D).

'PQ_D' can be calculated using Equation (23). The information required to utilize Equation (20) will be found in the Table 26, Table 28, and Table 29. Post assessment, the 'PQ_D' results obtained for Series A and Series B is shown in the Table 30.

Table 30 'PQ_D' results for Series A and Series B

	Series A	Series B
Q	0.70	0.76
PT_D	0.71	0.81
PQ_D	0.50	0.62

*6.1.4.4 Disassemblability (**EoL_D**)*

Disassemblability can be assessed by using the Equation (24). The information required to utilize this equation Table 27 and Table 30. Results calculated are shown in Table 31.

Table 31 EoL_D assessment for Series A and Series B

	Series A	Series B
PD_D	0.84	0.88
PQ_D	0.50	0.62
EoL_D	**0.62**	**0.73**

Final assessment implies that Series B is more easily disassembled compared to Series A.

6.2 Remanufacturability assessment

Methodology for Remanufacturability has been discussed in the Chapter 4. According to that methodology, a step-by-step assessment of design, quality and process related aspects will follow. Chapter 5 presents the information recorded through on-the-floor observations and expert opinion at SRC (*i.e.* Crew, upper management and engineering who are very familiar with SERIES A and SERIES B product type). This information will be used to exercise relevant metrics in this Section as per the methodology.

6.2.1 *PHASE I: Product Design Assessment*

6.2.1.1 Product Complexity for Remanufacturability (PC_R)

‘PC_R’ can be assessed with the help of Equation (27). Fastener Complexity in the case for disassembly and remanufacturing are the same. Thus, F_C for Series A and B are already known as 0.51 and 0.52 respectively (See section 6.1.1.1). As the depth of inspection activities differ during disassembly and remanufacturing, ‘NR_C’ will be assessed in this section using Equations (25) and (26). ‘NR_C’ for A and B can be found in Table 32 and

Table 33, respectively.

Table 32 Non -fastener complexity assessments for Series A.

u	Part	Qty	W_u	I_u	T_u	Score
1	Cylinder head	1	0.81	7	37	0.66
2	Hex Plug	1	0.00	2	2	0.00
3	Intake Seat	2	0.09	4	10	0.06
4	Exhaust Seat	2	0.09	4	10	0.06
					NR_C	**0.77**

Table 33 Non-fastener complexity assessments for Series B.

u	Part	Qty	W_u	I_u	T_u	Score
1	Cylinder head	1	0.56	7	37	0.46
2	Spark Plug Socket	1	0.22	1	10	0.19
3	Spark Plug Flange	1	0.02	1	7	0.01
4	Intake Seat	2	0.06	4	10	0.04
5	Exhaust Seat	2	0.15	4	10	0.09
					NR_C	**0.79**

Series B has a higher non-fastener complexity rating compared to Series A which implies that the elaborate inspection for Series B requires lesser effort compared to that of Series A. Hence, since F_C and NR_C are known from Table 19, Table 20, Table 32, and

Table 33, 'PC_R' can be computed using Equation (27). The results obtained are shown in Table 34.

Table 34 'PC_R' assessment for Series A and Series B

	Series A	Series B
NR_C	0.77	0.79
F_C	0.52	0.51
z_1	0.79	0.79
z_2	0.21	0.21
PC_R	**0.76**	**0.78**

As per the results, Series B has a better product complexity rating compared to Series A.

6.2.1.2 Product Accessibility (PA)

As the component geometry remains constant between the disassembly and remanufacturing phases, the PA will also remain the same. Hence, results from section 6.1.1.2 will apply.

6.2.2 *PHASE II: Process Technology Assessment*

6.2.2.1 Remanufacturing Score (RT)

Like Disassembly score, actual time for the overall batch is assessed based on an equation expressed in terms of 'Q_R'. This equation is obtained from the regression analysis of the 'Q_R' and $Time_R$ readings for each core (See Appendix I , appendix j, and Table 26). The predictive expressions of thus obtained for the actual time are shown in Equation (45) and (46) for Series A and B respectively.

$$T_{RT\ for\ Series\ A} = -1086.4 * Q + 831.11 \tag{51}$$

$$T_{RT for\ Series\ B} = 114.25 * Q - 1.63 \tag{52}$$

Based on Equation (45) and (46), assembly time obtained for Series A and B are **71** minutes and **82** minutes respectively. Results for Quality of return index are discussed in section 6.2.3 for the sake of consistency. Planned assembly time for Series A and Series B are **60** minutes and **75** minutes respectively. Hence, assessed results of 'A' for both the products types are shown in the Table 35.

Table 35 'RT**'** rating **-** Series A and B

	Series A	Series B
Actual (min)	71	82
Planned (min)	60	75
RT	**0.82**	**0.91**

6.2.2.3 Remanufacturing Effort Index (ER)

Remanufacturing Effort (E_R) of Series A and B is assessed in a slightly different manner compared to 'E_D'. The only difference is that all the steps in the process of remanufacturing are scored based on the scheme proposed by Das & Naik, (2002) as opposed to 'E_D' where only the steps for disassembly were considered. These scores are shown in Appendix O and Appendix P for Series A and B respectively. 'E_R' results are assessed based on the data listed in these appendices and on Equation (30). Results obtained are shown in the Table 36 for Series A and Series B respectively.

Table 36 'E_R' results for Series A & B

	Series A	**Series B**
E_{RA}	983.3	1076.9
E_{RMin}	692.6	768.6
E_{RMax}	2168	2412
E_R	**0.80**	**0.81**

6.2.2.4 Refurbish Index (RF)

Refurbish Index can be calculated with the help of Equation (32). The results obtained are shown in the Table 37 for Series A and Series B respectively.

Table 37 'RF' results for Series A & B

	Series A	Series B
R	1	3
N	42	47
RF	**0.98**	**0.94**

Series A has a higher 'RF' than SERIES B since the number of parts refurbished in the remanufacturing of Series A are lesser compared to that of Series B.

6.2.2.5 Cleaning Index (CL)

The prioritization matrix to establish the scores for each cleaning activity is shown in Table 11. After the scoring of individual components, a total score is derived by summing up all the individual component scores. This is applicable in the case of determining actual score (CL_a) and ideal score (CL_b) for the product. Then, Equation (34) is used to calculate the cleaning index (CL). The results are shown in the Table 38 and Table 39 for Series A and B respectively**.**

Table 38 'CL' assessment for Series A

S.no	Part	Qty	Actual	Actual*Qty	Ideal	Ideal*Qty
1	Cylinder head	1	34	34	29	29
2	Spring Retainer	4	1	4	1	4
3	Screw Plug	1	1	1	1	1
			CL_a	39	CL_b	34
			CL		**0.87**	

Table 39 'CL' assessment for Series B

S.no	Part	Qty	Actual	Actual*Qty	Ideal	Ideal*Qty
1	Cylinder head	1	34	34	29	29
2	Spark Plug Socket	1	1	1	1	1
3	Spark Plug Sleeve	1	1	1	1	1
4	Spring Retainer	4	1	4	1	4
5	Stud	2	1	2	1	2
			CL_a	42	CL_b	37
			CL		**0.88**	

The cleaning investment required for both the product types is very similar.

6.2.2.6 Inspection & Testing Index (IT)

SRC uses 3 activities for carrying out the Inspection and Testing of several components of Series A and B. Activities are Magnetic Particle Inspection (MPT), Manual Tooling inspection (Tool) and Pressure Testing (PT). Based on the feedback from SRC, Tool and PT setup require the same amount of investment. Based on the investment, the prioritization matrix established is shown in the Table 12. After establishing the scores for each activity in Table 12, each component is rated based on whether it is inspected/tested or not. Using the Equation (37), **'IT'** can be calculated. The results for both Series A and B are shown in Table 40 and Table 41 the respectively.

Table 40 'IT' assessment for Series A

S.no	Part	Qty	Actual	Actual*Qty	Ideal	Ideal*Qty
1	Cylinder head	1	9	9	4	4
2	Screw Plug	1	1	1	1	1
3	Intake Seat	2	1	2	1	2
4	Exhaust Seat	2	1	2	1	2
			IT_a	14	IT_b	9
			IT		**0.64**	

Table 41 ‘IT’ assessment for Series B

S.no	Part	Qty	Actual	Actual*Qty	Ideal	Ideal*Qty
1	Cylinder head	1	9	9	4	4
2	Spark Plug Socket	1	1	1	1	1
3	Spark Plug Sleeve	1	1	1	1	1
4	Intake Seat	2	1	2	1	2
5	Exhaust Seat	2	1	2	1	2
6	Stud	2	1	2	1	2
			IT_a	17	IT_b	12
			IT		**0.71**	

Series B is assessed to have a higher **IT** index compared to Series A. This is because Series A components require more inspection and testing activities compared to that of Series B components.

6.2.3 *PHASE III: Incoming Quality Assessment*

Quality index for remanufacturability (‘Q_R’) is computed using Equations (38) and (18). Here, ‘c_N’ has already been computed and shown in the Table 6 and Table 7 for Series A and B respectively. The next step is to gather the data for individual cores by establishing quality grading information (q_{RN}). In this case study, ‘q_{RN}’ for each product type is recorded by tracking 30 individual cores on the floor shop. The ‘q_{RN}’ ratings for each component of all the 30 cores can be found in the Appendix L. Incoming Quality can be assessed using the Equation (38). Results are shown in Table 42. ‘Q_R’ is assessed for each individual core and then averaged for all the cores to give a batch level ‘Q_R’.

Table 42 Core wise and Batch wise ‘Q_R’ results for Series A and B.

Order/Core	Order Specific ‘Q_R’		Order/Core	Order Specific ‘Q_R’	
	Series A	Series B		Series A	Series B
1	0.70	0.76	16	0.69	0.75
2	0.70	0.76	17	0.69	0.63
3	0.70	0.76	18	0.69	0.76
4	0.70	0.76	19	0.70	0.76
5	0.70	0.76	20	0.70	0.76
6	0.69	0.76	21	0.70	0.76
7	0.69	0.76	22	0.70	0.76
8	0.70	0.76	23	0.70	0.76
9	0.70	0.76	24	0.70	0.15
10	0.70	0.76	25	0.70	0.76
11	0.70	0.76	26	0.70	0.75
12	0.70	0.75	27	0.70	0.76
13	0.70	0.63	28	0.70	0.75
14	0.70	0.76	29	0.70	0.76
15	0.70	0.75	30	0.70	0.76
Batch Average ‘Q_R’				**0.70**	**0.73**

6.2.4 *PHASE IV: Consolidated Index Assessment*

6.2.4.1 Product Feature Index for remanufacturability (PD_R)

Product Feature Index for remanufacturability (PD_R) can be assessed using Equation (39). The usage of equation requires information from Table 34, Table 61, and Table 62 (See Appendix H). Upon calculation, the results obtained are shown in Table 43.

Table 43 ‘PD_R’ assessment for Series A and B

Metric	Series A	Series B
PA	0.87	0.90
PC_R	0.76	0.78
PD_R	**0.81**	**0.84**

As per the assessment, Series B seems to be more easily remanufacturable compared to Series A based on the product design.

6.2.4.2 Process Technological Capability for Remanufacturability (PT_R)

Process Technological Capability for remanufacturability (PT_R) can be assessed with the Equation (40). Prior to this, a prioritization matrix will have to be established to deliver the weights for all the six sub-aspects (*i.e.* **RT, E_R, RF, CL** and **IT)**. This matrix is shown in Table 10. With the weights and the results for each of the sub-aspect known, it is possible to assess 'PT_R'. Results for Series A and B are shown in Table 44 respectively.

Table 44 'PT_R' results for Series A & B

Process	Series A			Series B		
	Scores	Weights	PT_R	Scores	Weights	PT_R
RT	0.82	*0.43*	**0.87**	0.91	*0.43*	**0.90**
RF	0.98	*0.35*		0.94	*0.35*	
CL	0.87	*0.18*		0.88	*0.18*	
IT	0.64	*0.04*		0.71	*0.04*	
ER	0.8	*0.00*		0.81	*0.00*	

6.2.4.3 Process-Quality Index for Remanufacturability (PQ_R)

Process Quality index for remanufacturability (PQ_R) can be assessed using the Equation (41). The information required for this equation can be found in the Table 26, and Table 44. Assessed results for 'PQ_R' are shown in Table 45.

Table 45 'PQ_R' results for Series A and B

Metric	**Series A**	**Series B**
Q_R	0.70	0.73
PT_R	0.87	0.90
PQ_R	**0.61**	**0.69**

6.2.4.4 Remanufacturability (EoL_{REM})

Remanufacturability assessment can be done using Equation (42). Information required to for this equation can be obtained from Table 43 and Table 45. The results are shown in the Table 46.

Table 46 'EoL_{REM}' assessments for Series A and Series B

	Series A	Series B
PD_R	0.81	0.84
PQ_R	0.61	0.69
EoL_{REM}	**0.70**	**0.74**

Series B has a higher remanufacturability rating compared to Series A. This implies that Series B is more easily remanufacturable compared to Series A given the current process layout, and quality of returns.

Chapter 7 Results, Discussion and Validation

This chapter attempts to showcase the results generated in chapter 6 while simultaneously presenting a discussion. The showcase attempts to succinctly compare the assessment results for Series A and Series B. Next, the validation of the methodology is presented against the expert opinion. The opinion is gathered from experts of different departments of the company who are well verse with of the two product types.

7.1 Results & Discussion

The proposed methodology for both the 'ilities' has been applied to assess the two product types (Series A and B) remanufactured at SRC. The results generated for disassemblability and remanufacturability have been showcased in Table 47 and Table 48 respectively. Both the product types have been listed side by side for comparison.

Table 47 Disassemblability Results

	Series A	Series B
EoL_D	0.62	0.73
PQ_D	0.50	0.62
PT_D	0.71	0.81
Q_D	0.70	0.76
PD_D	0.84	0.88
PA	0.87	0.90
PC_D	0.82	0.87
D	0.70	0.81
E_D	0.83	0.84

The results listed in Table 47 have been retrieved from Table 23, Table 24, Table 25, Table 26, Table 27, Table 28, Table 29, Table 30, Table 31, Table 61, and Table 62. Results indicate that, Series B has a superior disassemblability index compared to Series A. This assessment is considering the design, incoming quality and process related characteristics that effect the disassemblability of both the product types. Referring to Table 47, it was observed from the results that series B has a superior 'EoL_D' assessment compared to Series A. This is a strong indication that Series B is better in all the three aspects of product, process and incoming quality of returns. This is reflected in the results of the specific consolidation metrics PQ_D, PT_D, and PD_D, respectively. Specially, the PT_D assessment for Series B is much higher than that of Series A. Thus, it implies that SRC is better facilitated to carry out disassembly for Series B. As per Table 47, 'E_D' assessment for both the product types is similar. Whereas, the 'D' assessment is significantly higher in the case of series B. As the investment weighting for disassembly time aspect is significantly higher compared to the disassembly effort, 'PT_D' is heavily influenced by the 'D' assessment.

Examining the design related metrics, it is seen that Series B has superior design, but not by a wide margin. Reason for such a gap is because of better component accessibility. Generally, disassembly process involves little or no inspection activities. Series B having a more geometrically complex head, making the inspection more complicated in comparison with Series A. But that doesn't diminish the product complexity rating for Series B significantly. This is because the critical dimensions that should be inspected during disassembly, are few and easily available. It was also observed that the incoming quality of Series B was slightly better than that of Series A. This mainly attributes to the fact that less number of components are rejected on Series B during disassembly. Both product types reject the same number of components due to the OEM guidelines. But since series B has a higher part count, impact of rejected components on the quality of return index is less significant as opposed to Series A.

Table 48 Remanufacturability Results

	Series A	Series B
EoL_{REM}	0.70	0.74
PQ_R	0.61	0.69
PT_R	0.87	0.90
Q_R	0.70	0.73
PD_R	0.81	0.84
PA	0.87	0.90
PC_R	0.76	0.78
RT	0.82	0.91
RF	0.98	0.94
CL	0.87	0.88
IT	0.64	0.71
E_R	0.80	0.81

The results listed in Table 48 have been retrieved from Table 34, Table 43, Table 44, Table 45, Table 46, Table 61, and Table 62. As per Table 48, the results indicate that Series B also has a better 'EoL_{REM}' assessment compared to Series A. But, this gap is not as wide as in the case of 'EoL_D'. As previously observed, 'PT_D' was impacting the 'EoL_D' assessment significantly for series B. But compared to disassembly, remanufacturing is more process intensive as it includes cleaning, inspection, refurbishing and testing. Given the more number of steps, higher remanufacturing effort is involved for both the product types. Certain excess components in the case of series B are difficult to handle which causes the gap in the effort index to reduce for remanufacturability. Cleaning requirements for Series B compared to Series A, are generally lower despite excess part count. Thus, Series B gets a marginally better score. Series A has a higher RF which contributes to closing the gap in the 'PT_R' assessment of both the product types. This is because Series A has lower number of components to be refurbished in comparison to its total part count. Series B has a significant advantage over Series A in terms of IT and RT. Several reasons for this could be the crew being more accustomed to Series B as it has a higher production volume, leading to less deviation from the planned remanufacturing time. Series B also requires relatively simpler methods of inspection thus, having a better IT assessment.

When taking the investment into account, remanufacturing time aspect weighs the highest followed by cleaning. Inspection and testing stands 3rd. This implies that the production line has a higher investment for the disassembly, assembly, and refurbishing activities as compared to cleaning, inspection and testing. Series B having a significantly higher RT assessment and marginally greater CL assessment propels its 'PT_R' results ahead of Series A. Indeed, IT assessment also further positively impacts this gap, but it is not significant due to lesser investment weight. In the design aspect, Series B again has higher assessment. This is because the non-fasteners in the case of Series B are simpler to inspect. Other than that, it has a marginally higher PA assessment. In terms of fastener complexity, both the product types are very similar. Therefore, the PC_R assessment despite the higher part count is still higher for Series B. The incoming quality for Series B has similar gaps as compared to series A for both the 'ilities'.

Figure 27 and Figure 28 illustrate a comparison between both the products types for case of disassemblability and remanufacturability, respectively. As discussed earlier, series B is far superior to Series A in the case of disassemblability. Although, such a trend exists in the case of remanufacturability, there is not a lot of gap in the assessment between the two product types.

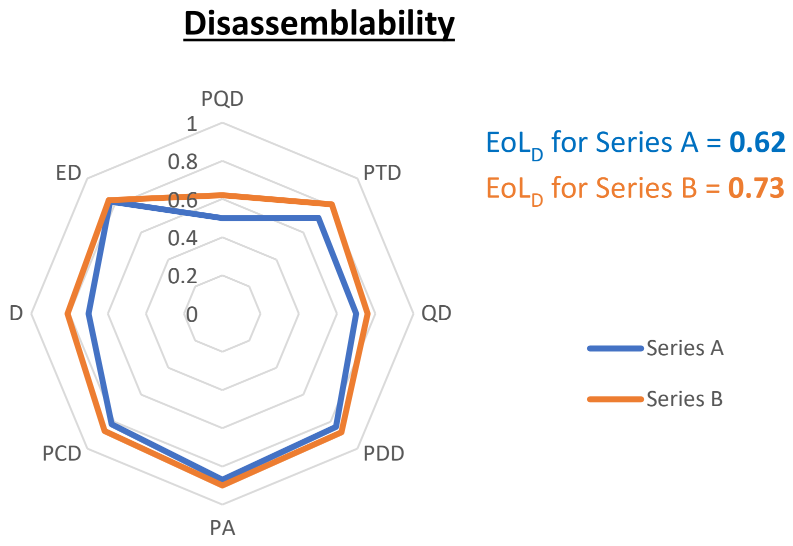


Figure 26 Disassemblability Comparison (Series A vs Series B)

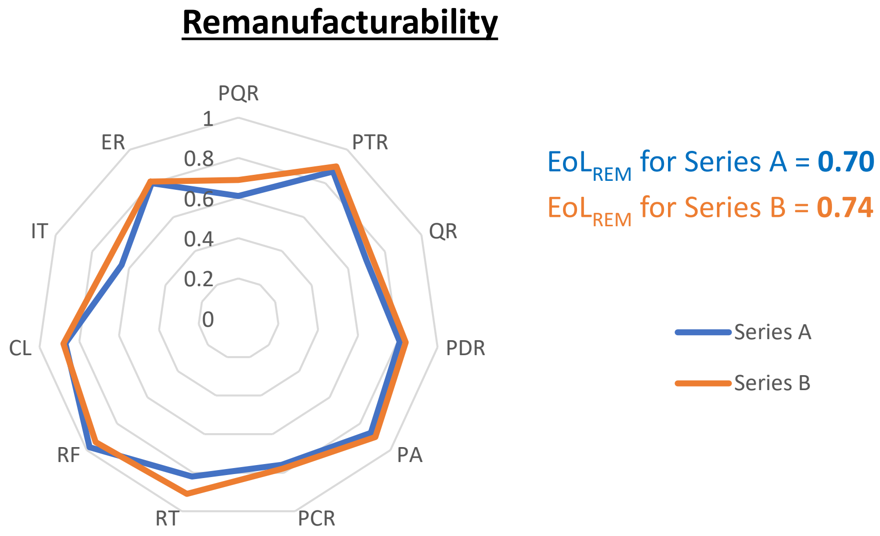


Figure 27 Remanufacturability Comparison (Series A vs Series B)

Process and incoming quality aspects for Series B in the case of disassemblability are vastly superior compared to that of Series A. Hence, Series B has significantly higher disassemblability than Series A. In the case of remanufacturability, overall, Series B is marginally better than Series A. Hence, both the products types in terms of remanufacturability are not significantly different.

7.2 Validation

To validate the approach proposed in this research, results of the assessment have been compared with the expert opinion (qualitative) retrieved from SRC. The experts chosen are vastly familiar with the two product types focused in this study. Also, to avoid the skewing of results because of the conscious or unconscious bias, experts were chosen from different departments of the company. The motivation to choose such a method for validation is as follows:

1. This is the only study that considers the product, process and incoming quality based aspects. Hence, comparison of results with a previously proposed study that considers a different combination aspect will not be a fair validation and can be misleading.
2. The company itself doesn't use any assessment scheme hence there are no benchmarks or methods to compare with.

Based on these two reasons, a validation strategy of comparing the results with that of the expert opinion was considered. Such basis of validation is not the strongest, but given the circumstances, it is reasonable. Also, expert opinion may or may not be affected due to an expert's domain of specialization. That is why, all the opinions gathered are from different departments of the company. The experts were asked to score both the product types, based on the ease of disassembly and remanufacturing, in their experience. The scoring requested was on a scale of 0-10. The results obtained are shown in Table 49.

Table 49 Qualitative scores for Series A & B

Sno.	Expert Opinion		EoL_D		EoL_{REM}	
	Designation	Title	Series A	Series B	Series A	Series B
1	Production Manager	Nathan	5.0	7.0	5.0	7.0
2	Manufacturing Engineer	Rodney	7.0	8.0	6.0	8.0
3	Team Lead	Rick	5.0	7.0	5.0	5.0
4	Sales Manager	Adam	4.0	6.0	7.0	4.0
5	Best Operator	Josh	5.0	7.0	6.0	7.0

To refine the results further, an average of ratings was taken for each product type under each 'ility'. The average EO ratings are shown in Table 50.

Table 50 Average Qualitative Scores

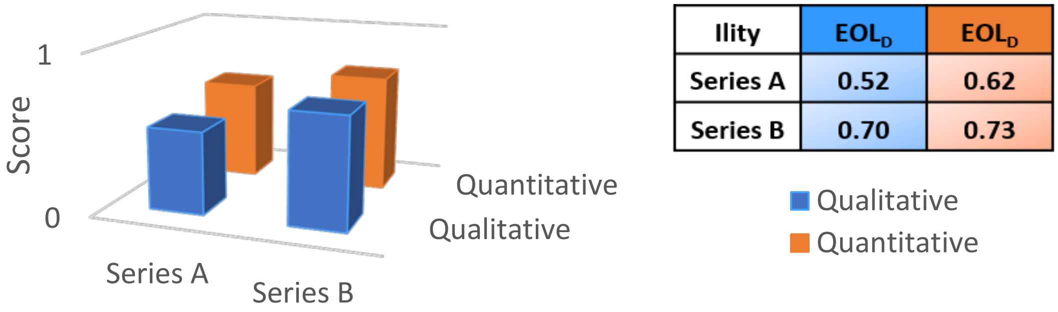
	DA	REM
Series A	5.2	5.8
Series B	7	6.2

As the opinions can be subjective, comparing the exact values of the results between qualitative and the proposed methodology (quantitative) is not reasonable. A more appropriate strategy is to compare the rate of change of scores from one product type to another, between qualitative and quantitative approach, respectively, under one ‘ility’. Next, the qualitative averages are brought to 0-1 scale from 0-10 scale by dividing the averages of both the product types by 10. The converted scores are shown in Table 51.

Table 51 Converted Scores of qualitative approach

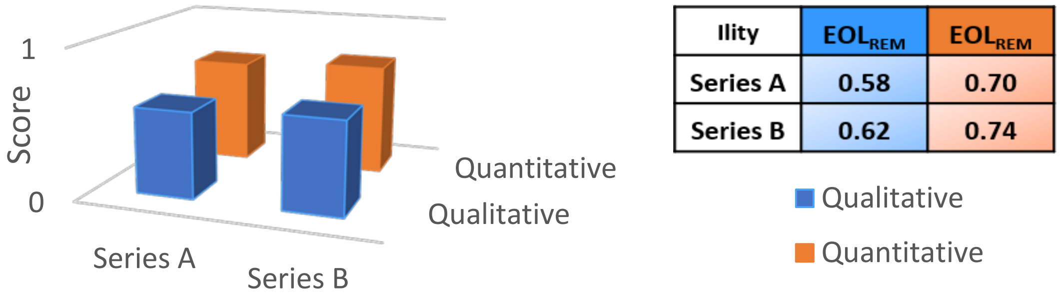
	DA	REM
Series A	0.52	0.58
Series B	0.70	0.62

With the scores established in Table 47, Table 48 and Table 51, rate of change of scores from one product type to another, between qualitative and quantitative approach under disassemblability is shown in Figure 29. It can be observed that both the methodologies show similar trends. Similar trend is shown in Figure 30, in case remanufacturability.



Ility	EOL_D	EOL_D
Series A	0.52	0.62
Series B	0.70	0.73

Figure 28 Disassemblability comparison of Qualitative & Quantitative Scores



Ility	EOL_{REM}	EOL_{REM}
Series A	0.58	0.70
Series B	0.62	0.74

Figure 29 Remanufacturability comparison of Qualitative & Quantitative Scores

The rate of change of scores between the two product types is nothing but the slope of line. In the case of both the ‘ilities’, two slopes exist; (1) Slope for qualitative results and (2) Slope for quantitative results. For disassemblability, the values for these slopes are assessed to be 0.6 and 0.9 for series A and B respectively. Likewise, for the case of remanufacturability, two slopes were determined to be 2.5 and 2.6, respectively. Since, the pair of slopes in case of both the ‘ilities’ are similar, it is appropriate to conclude that the rate of change of scores through the product types between both qualitative and quantitative approach is similar. This similarity exists in case of both the ‘ilities’. Even though the qualitative scores are subjective, a relative judgement between the two product types based on the experience of experts is reflected from the slope of the line. This slope is like that of quantitative approach for both the ‘ilities’. Hence, it can be generally accepted, that the proposed methodology reflects an assessment relevant to the experience of the experts during disassembly and remanufacturing.

Chapter 8 Conclusion and Future Work

8.1 Conclusion

A consequence of stricter regulations, depleting availability of landfill spaces and the alarming rate of resource utilization, ‘PU’ stage of products have become pivotal for various take-back legislations to promote the implementation of close-loop material flow. This has resulted in many organization adapting various EoL strategies. Remanufacturing being one of the most common form of EoL strategy has sparked a lot of research in the past two decades. One of the most prominent challenges identified by the previous studies, was quantification of the ability to implement to these EoL strategies, with the help of explicit metrics and relevant factors. From the research perspective, the proposed methodology contributes an identified set of relevant factors and metrics that should be considered while assessing the disassemblability and remanufacturability of a product. This satisfies the two primary research objectives of this study. Moreover, the proposed methodology considers a combination of aspects that has not been considered by the previous studies. While doing so, explicit metrics for the incoming quality aspect were introduced. Thus, the identified research gaps during the literature review have also been addressed. The ‘ility’ assessment culminates into a single consolidated score which reflects the overall impact of the underlying metrics. As observed through application, the metrics used are simple to implement and build upon data that is easy to gather. Considering such experiences, all the methodological objectives in terms of the intended strengths, have also been satisfied. From validation, it was established that the methodology captures and reflects the information, similar to the expert perspective, pertaining to the disassembly and remanufacturing of both the product types. Out of the two product types, the latest generation was assessed to have a higher disassemblability and remanufacturability. Hence, higher rate of remanufacturing more for Series B recommended. From the industrial perspective, such a methodology enables the remanufacturers to make better decisions regarding selecting which product to disassemble and/or remanufacture. By doing so they benefit in two probable scenarios; (1) new product/variant introduction, and (2) existing product/variant prioritization. Furthermore, the data collection done in the case of this methodology helps the user to understand and track the flow of investment, and losses (due to process times, scrap rate and line ergonomics, if any).

8.2 Future Work

Future work for this study includes the following:

1. Application of this approach for various other products, preferably across different industries with the aim to further validate the methodology.
2. To incorporate factors like operator expertise and operator training that might affect the complexity and accessibility of a product.
3. The incoming quality metric proposed in this research, can be extended further to rate the incoming components in a more comprehensive manner which is further than just recording rejection and acceptance.
4. Another scope includes identification of data friendly factors and metrics for remaining life and demand related characteristics to expand the comprehensiveness of this study.
5. Lastly, to use this study as the foundation for developing methodology for other 'ilities' like recoverability, reusability, etc.

Appendix A: List of Abbreviations

TLCA – Total Lifecycle Approach

EoL – End-of-Life

KPI – Key Performance Indicators

DoF – Degree of Freedom

BOM – Bill of Materials

DFR – Design-for-Remanufacturing

DFA – Design-for-Assembly

OEM - Original Equipment Manufacturer

REMAN - remanufacturing

DAS - disassembly

AS – assembly

POC – Probability of occurrence

CI – Cost implications

Appendix B: List of Notations

EoL_D – Disassemblability

PD_D – Product Feature Score for Disassembly

PA – Product Accessibility

N – Total Number of Components

a_N – N^{th} Component's Accessibility Index

A_N – N^{th} Component's Adjusted a_N

Min. (A_N) – Minimum A_N

Max. (A_N) – Maximum A_N

A_N' – N^{th} Component's Accessibility Score

Avg. (A_N') – Average Component Accessibility Score

PC_D – Product Complexity for Disassemblability

i – type of fastener

f_i – BOM quantity for the i^{th} type

j – category of the i^{th} type of fastener

k – U-rating of the i^{th} type of fastener

F_A – Actual Fastener Index

F_I – Ideal Fastener Index

Min. (j) – Minimum category of fastener

Min. (k) – Minimum U-rating of fastener

F_C – Fastener Complexity Score

ND_C – Non-Fastener Complexity Score during disassembly

l – Number of Inspected Non-Fasteners during disassembly

W_l – Cost Based Weight for k^{th} Non-Fastener during disassembly

I_l – Number of Inspected Features for k^{th} Non-Fastener during disassembly

T_l – Total Number of Features available for Inspection of k^{th} Non-Fastener during disassembly

PQ_D – Process-Quality Score for disassemblability

Q_D – Value based quality of return for disassemblability

q_{DN} – Quality based binary rating for the N^{th} component during disassembly

c_N – Relative Cost Based Weight for the N^{th} component

PT_D – Process Technological Capability for Disassemblability

D – Disassembly Score

$Time_D$ – Actual Disassembly Time

$Time_{PD}$ – Planned Disassembly Time

E_D – Disassembly Effort Index

E_{DA} – Actual Effort Score for disassembly

$E_{DMax.}$ – Maximum Effort Score for disassembly

$E_{DMin.}$ – Minimum Effort Score for disassembly

W_D – Investment based Weight for Disassembly

W_{ED} – Investment based Weight for Disassembly Effort

EoL_{REM} – Remanufacturability

PQ_R – Process-Quality Score for Remanufacturability

Q_R – Value based quality of return for Remanufacturability

q_{RN} – Quality based binary rating for the N^{th} component during remanufacturing

PT_R – Process Technological Capability for Remanufacturability

PD_R – Product Feature Score for Remanufacturability

PC_R – Product Complexity for Remanufacturability

NR_C – Non-Fastener Complexity Score during remanufacturing

u – Number of Inspected Non-Fasteners during remanufacturing

W_u – Cost Based Weight for k^{th} Non-Fastener during remanufacturing

I_u – Number of Inspected Features for k^{th} Non-Fastener during remanufacturing

T_u – Total Number of Features available for Inspection of k^{th} Non-Fastener during remanufacturing

E_R – Remanufacturing Effort Index

E_{RA} – Actual Effort Score for remanufacturing

$E_{RMax.}$ – Maximum Effort Score for remanufacturing

$E_{RMin.}$ – Minimum Effort Score for remanufacturing

RT – Remanufacturing Score

$Time_{RT}$ – Remanufacturing Time

$Time_{PRT}$ – Planned Remanufacturing Time

RF – Refurbish Index

R – Number of Refurbished Components

CL – Cleaning Index

CL_b – Product-Ideal Cleaning Score

CL_a – Product-Actual Cleaning Score

IT – Inspection and Testing Index

IT_b – Product-Ideal Inspection & Testing Score

IT_a – Product-Actual Inspection & Testing Score

W_{RT} – Relative investment based weight for remanufacturing facility

W_{ER} - Investment based weight for remanufacturing effort for remanufacturability

W_{REF} – Relative Investment based Weight for Refurbishing facility

W_C – Relative Investment based Weight for Cleaning facility

W_{IT} – Relative Investment based Weight for Cleaning facility

Appendix C: Complete List of Factors from Literature Review

Table 52 - List of factors Identified from the Literature Review

Sno.	Factors	(Fang, et al. 2015)	(Armacost et al. 2005)	(Zhang et al., 2013)	(Mangun & Thurston, 2002)	(Kaebernick et al. 2003)	(Kaebernick and Anityasari 2008)	(Robotis et al. 2012)	(B. Lu et al., 2014)	(Amezquita et al., 1995)	(Ijomah, McMahon, Hammond, & Newman, 2007)	(Bras & Hammond, 1996)	(Sundin & Bras, 2005)	(Shu & Flowers, 1999)	(Lebreton & Tuma, 2006)	(Bao, Uppuluri, Anityasari, & Manmek, 2006)	(Yao, Cui, Wang, & Shi, 2014)	(Feng et al. 2013)	(Polotskiet al. 2015)	(Johnson & Wang, 1998)	(Kim & Goyal, 2011)	(Kwak & Kim, 2010)	(Umeda, Fukushige, Mizuno, & Matsuyama, 2013)	(Soh et al., 2015)	(Desai & Mital, 2003)	(Tian et al., 2013)	(Gungor & Gupta, 1999)	(Fujimoto et al. 2001)	(Kroll & Carver, 1999)	(Gadh et al., 1998)	(Suga,at al. 1996)	(Aras et al., 2004)	(Giudice & Kassem, 2009)	(Wang,et al. 2012)	(Mabee et al. 1999)
1	DA complexity	•									•													•											
2	Types of Fasteners																													•					
3	Unfastening Difficulty																																		
4	Fastener Accessibility	•																						•				•		•			•		•
5	Disassemblability	•																						•											
6	Recoverability																							•											
7	Quality of Returns											•										•										•			
8	Cost of Returns																																		
9	remanufactured products cost																																		
10	Remanufacturing Cost																																		
11	Cost of Cleaning		•																																•
12	Number of Inspected Non-fasteners																																		•
13	Direct Cost			•					•																										
14	Product & component reliability				•																	•													
15	Product Cost				•				•		•			•		•																			
16	Operating Time				•																														
17	Component manufacturing cost				•				•							•																			
18	Component AS cost				•				•																										
19	Component take back cost				•				•																										

Table 53 - Continued

Sno.	Factors	(Fang, et al. 2015)	(Armacost et al. 2005)	(Zhang et al., 2013)	(Mangun & Thurston, 2002)	(Kaebernick et al. 2003)	(Kaebernick and Anityasari 2008)	(Robotis et al. 2012)	(B. Lu et al., 2014)	(Amezquita et al., 1995)	(Ijomah et al., 2007)	(Bras & Hammond, 1996)	(Sundin & Bras, 2005)	(Shu & Flowers, 1999)	(Lebreton & Tuma, 2006)	(Bao et al., 2006)	(Yao et al., 2014)	(Feng et al. 2013)	(Polotskiet al. 2015)	(Johnson & Wang, 1998)	(Kim & Goyal, 2011)	(Kwak & Kim, 2010)	(Umeda et al., 2013)	(Soh et al., 2015)	(Desai & Mital, 2003)	(Tian et al., 2013)	(Gungor & Gupta, 1999)	(Fujimoto et al. 2001)	(Kroll & Carver, 1999)	(Gadh et al., 1998)	(Suga,at al. 1996)	(Aras et al., 2004)	(Giudice & Kassem, 2009)	(Wang,et al. 2012)	(Mabee et al. 1999)
20	Component REMAN cost				•	•			•					•		•						•													
21	Component DA cost				•				•											•															
22	life of component				•																														
23	Avg. use rate				•																														
24	Number of Life Cycles				•																														
25	Product Gain					•	•				•					•																			
26	Product value					•										•																			
27	Product Lifecycle Cost					•	•									•																			
28	Product Technical Effectiveness					•																													
29	Market price					•	•		•		•					•																			
30	Quality evaluation						•																												
31	Remaining life						•																												
32	Est. used life						•																												
33	Repair cost							•	•																										
34	Holding Cost							•	•									•			•														
35	Replacement cost							•	•																										
36	Optimal Repair							•																											
37	Reusability investment decision							•																											
38	Replacement decision							•																											
39	REMAN cost uncertainty							•																											

Table 54 - Continued

Sno.	Factors	(Fang, et al. 2015)	(Armacost et al. 2005)	(Zhang et al., 2013)	(Mangun & Thurston, 2002)	(Kaebernick et al. 2003)	(Kaebernick and Anityasari 2008)	(Robotis et al. 2012)	(B. Lu et al., 2014)	(Amezquita et al., 1995)	(Ijomah et al., 2007)	(Bras & Hammond, 1996)	(Sundin & Bras, 2005)	(Shu & Flowers, 1999)	(Lebreton & Tuma, 2006)	(Bao et al., 2006)	(Yao et al., 2014)	(Feng et al. 2013)	(Polotskiet al. 2015)	(Johnson & Wang, 1998)	(Kim & Goyal, 2011)	(Kwak & Kim, 2010)	(Umeda et al., 2013)	(Soh et al., 2015)	(Desai & Mital, 2003)	(Tian et al., 2013)	(Gungor & Gupta, 1999)	(Fujimoto et al. 2001)	(Kroll & Carver, 1999)	(Gadh et al., 1998)	(Suga,at al. 1996)	(Aras et al., 2004)	(Giudice & Kassem, 2009)	(Wang,et al. 2012)	(Mabee et al. 1999)
40	Collection cost							•																											
41	Ease of disassembly									•																									
42	Ease of cleaning									•																									
43	Ease of inspection		•							•																									
44	Ease of replacement									•																									
45	No. of reusable non-fasteners									•																									
46	No. of modular non-fasteners									•																									
47	Number of fasteners									•																	•		•	•					
48	Number of interfaces									•																									
49	technological advancement										•																								
50	Demand Rate										•				•																				
51	Reman lead time										•																								
52	IP Conflicts										•																								
53	Tot. no. of parts										•													•			•		•						
54	Operator skill requirement										•														•										
55	Assembly efficiency											•																							
56	Disassembly efficiency											•																							
57	Reassembly efficiency											•																							
58	Inspection efficiency											•																							•
59	Testing efficiency											•																							•

Table 55 - Continued

Sno.	Factors	(Fang, et al. 2015)	(Armacost et al. 2005)	(Zhang et al., 2013)	(Mangun & Thurston, 2002)	(Kaebernick et al. 2003)	(Kaebernick and Anityasari 2008)	(Robotis et al. 2012)	(B. Lu et al., 2014)	(Amezquita et al., 1995)	(Ijomah et al., 2007)	(Bras & Hammond, 1996)	(Sundin & Bras, 2005)	(Shu & Flowers, 1999)	(Lebreton & Tuma, 2006)	(Bao et al., 2006)	(Yao et al., 2014)	(Feng et al. 2013)	(Polotskiet al. 2015)	(Johnson & Wang, 1998)	(Kim & Goyal, 2011)	(Kwak & Kim, 2010)	(Umeda et al., 2013)	(Soh et al., 2015)	(Desai & Mital, 2003)	(Tian et al., 2013)	(Gungor & Gupta, 1999)	(Fujimoto et al. 2001)	(Kroll & Carver, 1999)	(Gadh et al., 1998)	(Suga,at al. 1996)	(Aras et al., 2004)	(Giudice & Kassem, 2009)	(Wang,et al. 2012)	(Mabee et al. 1999)
60	Cleaning efficiency											•																							
61	Refurbish efficiency											•																							
62	Replaced Key parts											•																							
63	Replaced Non-key parts											•																							
64	Ease of Identification												•																						
65	Ease of Verification												•																						
66	Ease of Access												•																						
67	Ease of Handling												•																						
68	Ease of Separation												•																						
69	Ease of Securing												•																						
70	Ease of Alignment												•																						
71	Ease of Stacking												•																						
72	Wear Resistance												•																						
73	Recycling cost													•																					
74	Maintenance Cost													•																					
75	On line Failure													•																					
76	Return timings & quantities														•																				
77	Reintegration potential														•																				
78	Product reliability															•																			
79	Material cost															•				•	•														

Table 56 - Continued

Sno.	Factors	(Fang, et al. 2015)	(Armacost et al. 2005)	(Zhang et al., 2013)	(Mangun & Thurston, 2002)	(Kaebernick et al. 2003)	(Kaebernick and Anityasari 2008)	(Robotis et al. 2012)	(B. Lu et al., 2014)	(Amezquita et al., 1995)	(Ijomah et al., 2007)	(Bras & Hammond, 1996)	(Sundin & Bras, 2005)	(Shu & Flowers, 1999)	(Lebreton & Tuma, 2006)	(Bao et al., 2006)	(Yao et al., 2014)	(Feng et al. 2013)	(Polotskiet al. 2015)	(Johnson & Wang, 1998)	(Kim & Goyal, 2011)	(Kwak & Kim, 2010)	(Umeda et al., 2013)	(Soh et al., 2015)	(Desai & Mital, 2003)	(Tian et al., 2013)	(Gungor & Gupta, 1999)	(Fujimoto et al. 2001)	(Kroll & Carver, 1999)	(Gadh et al., 1998)	(Suga,at al. 1996)	(Aras et al., 2004)	(Giudice & Kassem, 2009)	(Wang,et al. 2012)	(Mabee et al. 1999)
80	Material service life																•																		
81	Material recoverability																•																		
82	Material efficiency																•																		
83	Accessibility																							•											
84	Demand rate																	•	•		•														
85	Return rate																	•																	
86	Product Deterioration rate																	•																	
87	Production rate																	•	•		•														
88	Production capacity																	•			•														
89	Remanufacturing capacity																	•																	
90	Serviceable inventory																	•	•																
91	Return inventory																		•															•	
92	Setup time																		•															•	
93	Setup cost																		•		•						•			•			•		
94	Tool Cost																										•			•			•		
95	Backlog cost																		•																
96	Reclamation value																			•															
97	Labor rate																			•										•			•	•	
98	Disposal cost																			•															
99	Profit Margin																			•	•														

Table 57 - Continued

Sno.	Factors	(Fang, et al. 2015)	(Armacost et al. 2005)	(Zhang et al., 2013)	(Mangun & Thurston, 2002)	(Kaebernick et al. 2003)	(Kaebernick and Anityasari 2008)	(Robotis et al. 2012)	(B. Lu et al., 2014)	(Amezquita et al., 1995)	(Ijomah et al., 2007)	(Bras & Hammond, 1996)	(Sundin & Bras, 2005)	(Shu & Flowers, 1999)	(Lebreton & Tuma, 2006)	(Bao et al., 2006)	(Yao et al., 2014)	(Feng et al. 2013)	(Polotskiet al. 2015)	(Johnson & Wang, 1998)	(Kim & Goyal, 2011)	(Kwak & Kim, 2010)	(Umeda et al., 2013)	(Soh et al., 2015)	(Desai & Mital, 2003)	(Tian et al., 2013)	(Gungor & Gupta, 1999)	(Fujimoto et al. 2001)	(Kroll & Carver, 1999)	(Gadh et al., 1998)	(Suga,at al. 1996)	(Aras et al., 2004)	(Giudice & Kassem, 2009)	(Wang,et al. 2012)	(Mabee et al. 1999)
100	Disassembly Sequence																			•															
101	Total reclaimed nf																			•															
102	Material value																			•															
103	Component weight																			•													•		
104	Disassembly time		•																	•						•	•		•					•	
105	Recovery rate																				•														
106	Time between orders																																		
107	Recycled non-fasteners count																																		
108	new component count																					•													
109	Residual Value																					•													
110	Difference in generation																					•													
111	Period of technical obsolescence																					•													
112	Reusability threshold																					•													
113	Recov. cost																					•													
114	Recovery profit																					•													
115	Process type for each component																						•												
116	Material Properties																						•												
117	DA Effort																							•							•				

Appendix D: Disassemblability analysis rating scheme

Table 58 Disassemblability analysis rating scheme (Desai & Mittal, 2003)

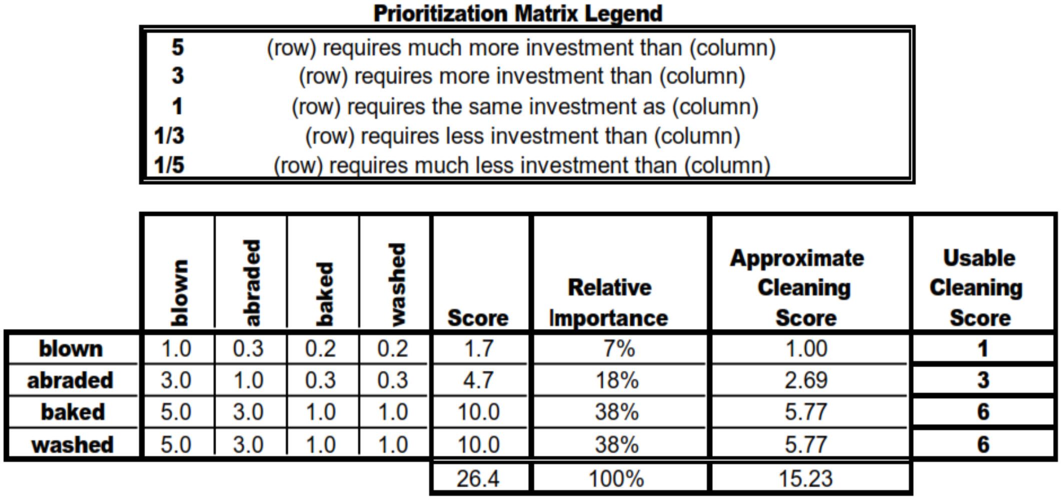
Design attribute	Design feature	Design parameters	Score	Interpretation
Disassembly force	Straight line motion without exertion of pressure	Push/pull operations with hand	0.5	Little effort required
			1	Moderate effort required
			3	Large amount of effort required
	Straight line and twisting	Twisting and push/pull operations with hand	1	Little effort required
			2	Moderate effort required
			4	Large amount of effort required
	Straight line motion with motion without pressure	Inter-surface friction and/or wedging	2.5	Little effort required
			3	Moderate effort required
			5	Large amount of effort required
	Straight line and twisting motions with exertion of pressure	Inter-surface friction and/or wedging	3	Little effort required
			3.5	Moderate effort required
			5.5	Large amount of effort required
	Twisting motions with pressure exertion	Material stiffness	3	Little effort required
			4.5	Moderate effort required
			6.5	Large amount of effort required
Material handling	Component Size	Component dimensions (very large or very small)	2	Easily grasped
			3.5	Moderately difficult to grasp
			4	Difficult to grasp
		Magnitude of weight	2	Light (o7.5 lb.)
			2.5	Moderately heavy (o17.5 lb.)
			3	Very heavy (o27.5 lb.)
	Component symmetry	Symmetric components are easy to handle	0.8	Light and symmetric
			1.2	Light and semi-symmetric
			1.4	Light and asymmetric
			2	Moderately heavy, symmetric
			2.2	Moderately heavy, semisymmetric
			2.4	Moderately heavy, asymmetric
			4.4	Heavy and symmetric
			4.6	Heavy and semi-symmetric
			5	Heavy and asymmetric

Table 59 Continued

Design attribute	Design feature	Design parameters	Score	Interpretation
Requirement of tools for disassembly	Exertion of force		1	No tools required
			2	Common tools required
			3	Specialized tools required
	Exertion of torque		1	No tools required
			2	Common tools required
			3	Specialized tools required
Accessibility of joints/grooves	Dimensions	Length, breadth, depth, radius, angle made with surface	1	Shallow and broad fastener recesses, large and readily visible slot/ recess in case of snap fits
			1.6	Deep and narrow fastener recesses, obscure slot/recess in case of snap fits
			2	Very deep and very narrow fastener recesses, slot for prying open snap fits difficult to locate
	Location	On plane surface	1	Groove location allows easy access
		On angular surface	1.6	Groove location is difficult to access. Some manipulation required.
		In a slot	2	Groove location very difficult to access
Positioning	Level of accuracy required to position the tool	Symmetry	1.2	No accuracy required
			2	Some accuracy required
			5	High accuracy required
		Asymmetry	1.6	No accuracy required
			2.5	Some accuracy required
			5.5	High accuracy required

Appendix E: Prioritization of Cleaning Processes

Table 60 Prioritization of Cleaning Processes (Bras and Hammond, 1996)

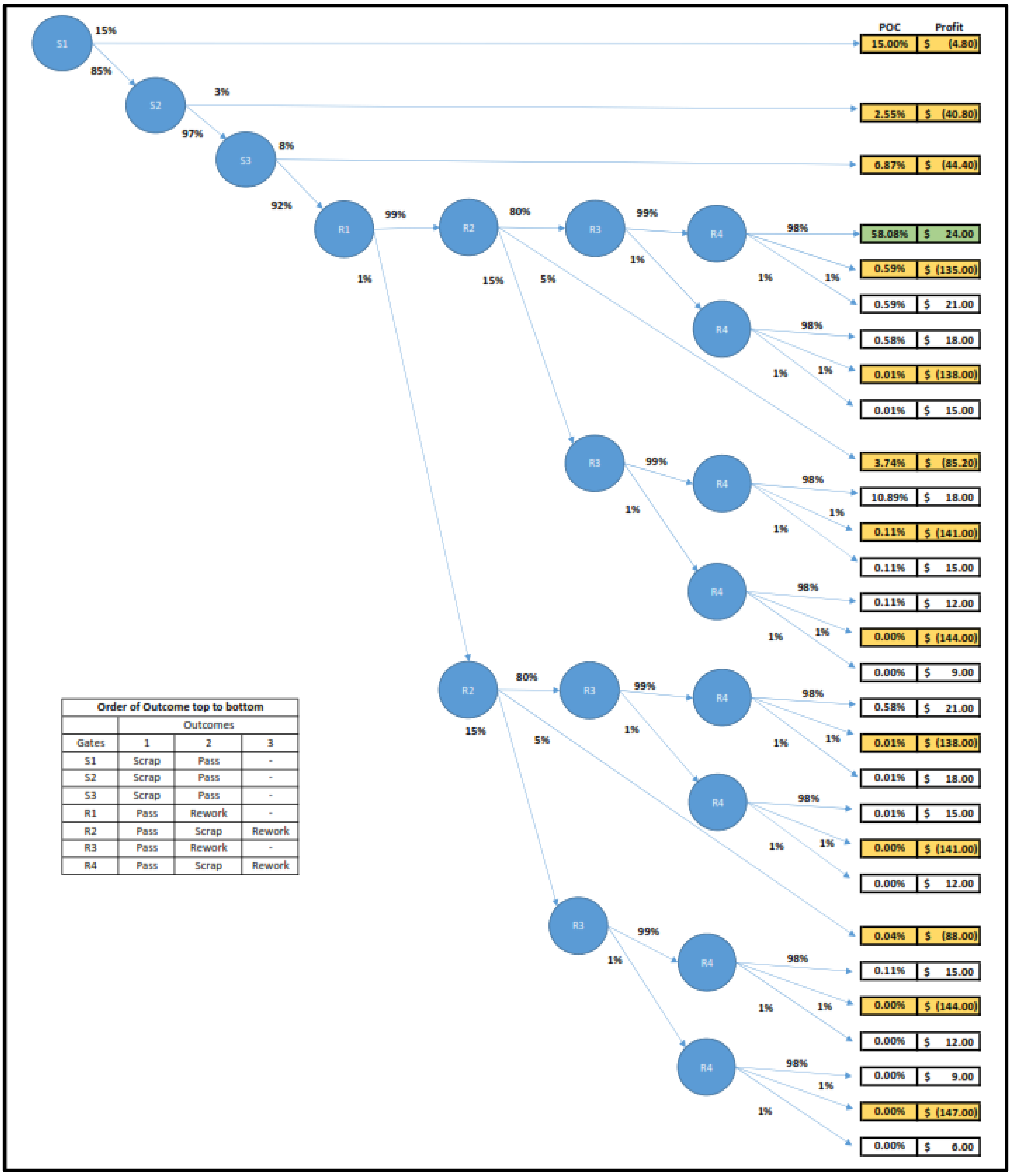


Prioritization Matrix Legend

5	(row) requires much more investment than (column)
3	(row) requires more investment than (column)
1	(row) requires the same investment as (column)
1/3	(row) requires less investment than (column)
1/5	(row) requires much less investment than (column)

	blown	**abraded**	**baked**	**washed**	**Score**	**Relative Importance**	**Approximate Cleaning Score**	**Usable Cleaning Score**
blown	1.0	0.3	0.2	0.2	1.7	7%	1.00	**1**
abraded	3.0	1.0	0.3	0.3	4.7	18%	2.69	**3**
baked	5.0	3.0	1.0	1.0	10.0	38%	5.77	**6**
washed	5.0	3.0	1.0	1.0	10.0	38%	5.77	**6**
					26.4	100%	15.23	

Appendix F: Probability Tree for Series A



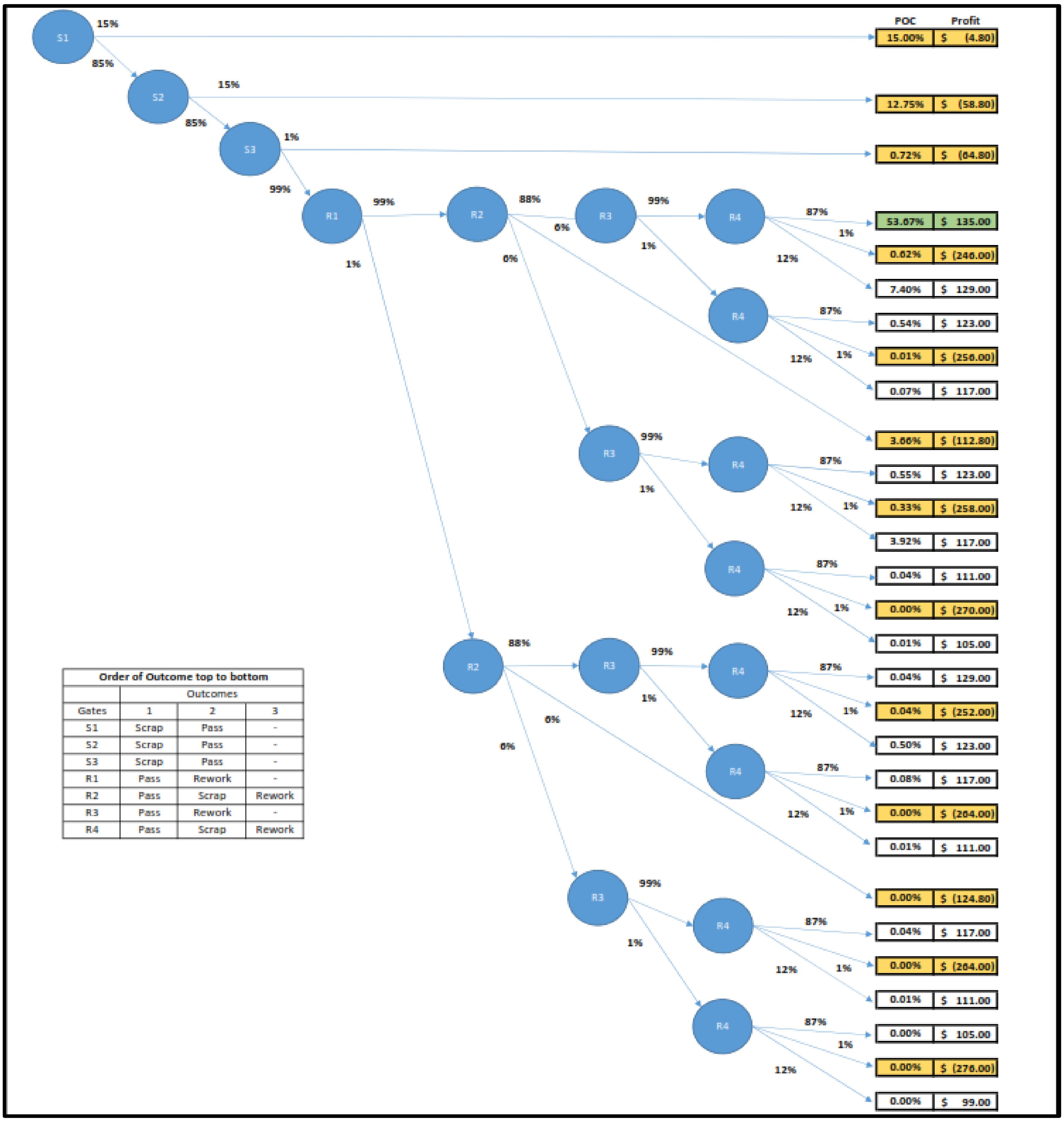
POC	Profit
15.00%	$ (4.80)
2.55%	$ (40.80)
6.87%	$ (44.40)
58.08%	$ 24.00
0.59%	$ (135.00)
0.59%	$ 21.00
0.58%	$ 18.00
0.01%	$ (138.00)
0.01%	$ 15.00
3.74%	$ (85.20)
10.89%	$ 18.00
0.11%	$ (141.00)
0.11%	$ 15.00
0.11%	$ 12.00
0.00%	$ (144.00)
0.00%	$ 9.00
0.58%	$ 21.00
0.01%	$ (138.00)
0.01%	$ 18.00
0.01%	$ 15.00
0.00%	$ (141.00)
0.00%	$ 12.00
0.04%	$ (88.00)
0.11%	$ 15.00
0.00%	$ (144.00)
0.00%	$ 12.00
0.00%	$ 9.00
0.00%	$ (147.00)
0.00%	$ 6.00

Order of Outcome top to bottom

	Outcomes		
Gates	1	2	3
S1	Scrap	Pass	-
S2	Scrap	Pass	-
S3	Scrap	Pass	-
R1	Pass	Rework	-
R2	Pass	Scrap	Rework
R3	Pass	Rework	-
R4	Pass	Scrap	Rework

Figure 30 Probability Tree for Series A

Appendix G: Probability Tree for Series B



POC	Profit
15.00%	$ (4.80)
12.75%	$ (58.80)
0.72%	$ (64.80)
53.67%	$ 135.00
0.62%	$ (246.00)
7.40%	$ 129.00
0.54%	$ 123.00
0.01%	$ (256.00)
0.07%	$ 117.00
3.66%	$ (112.80)
0.55%	$ 123.00
0.33%	$ (258.00)
3.92%	$ 117.00
0.04%	$ 111.00
0.00%	$ (270.00)
0.01%	$ 105.00
0.04%	$ 129.00
0.04%	$ (252.00)
0.50%	$ 123.00
0.08%	$ 117.00
0.00%	$ (264.00)
0.01%	$ 111.00
0.00%	$ (124.80)
0.04%	$ 117.00
0.00%	$ (264.00)
0.01%	$ 111.00
0.00%	$ 105.00
0.00%	$ (276.00)
0.00%	$ 99.00

Order of Outcome top to bottom			
	Outcomes		
Gates	1	2	3
S1	Scrap	Pass	-
S2	Scrap	Pass	-
S3	Scrap	Pass	-
R1	Pass	Rework	-
R2	Pass	Scrap	Rework
R3	Pass	Rework	-
R4	Pass	Scrap	Rework

Figure 31 Probability Tree for Series B

Appendix H: Accessibility table

Table 61 Accessibility calculations for Series A

S.no	Disassembly Sequence	Part	Qty	X	Y	Z	Δx	Δy	Δz	Δx/X	Δy/Y	Δz/Z	log2 (Δx/X)	log2 (Δy/Y)	log2 (Δz/Z)	Iacc	Iacc*Qty	Iacc Rating
1	ABCDEFGHIJKLMNOP: Q	Keepers	8	0.50	0.88	0.75	0.01	0.01	0.01	0.02	0.01	0.01	-5.64	-6.45	-6.23	18.32	146.59	0.00
2	ABCDEFGHIJKLMNO: P	Spring Retainer	4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
3	ABCDEFGHIJKLMN: O	Exh. Outer Spring	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
4	ABCDEFGHIJKLM: N	Exh. Inner Spring	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
5	ABCDEFGHIJKL:M	Intake Outer Spring	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
6	ABCDEFGHIJK: L	Intake Inner Spring	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
7	ABCDEFGHIJ: K	Washer	4	0.25	0.25	0.13	0.25	0.25	0.10	1.00	1.00	0.80	0.00	0.00	-0.32	0.32	1.29	0.99
8	ABCDEFGHI: J	Exhaust Valve	2	11.00	3.00	3.00	2.50	0.01	0.01	0.23	0.00	0.00	-2.14	-8.23	-8.23	18.60	37.20	0.75
9	ABCDEFGH: I	Intake Valve	2	11.00	3.00	3.00	2.50	0.01	0.01	0.23	0.00	0.00	-2.14	-8.23	-8.23	18.60	37.20	0.75
10	ABCDEFG:H	Valve Guide Seal	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
11	ABCDEF: G	Valve Guide Seal	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
12	ABCDE: F	Intake Sleeve	2	4.75	1.00	1.00	1.38	1.00	1.00	0.29	1.00	1.00	-1.79	0.00	0.00	1.79	3.58	0.98
13	ABCD: E	Exhaust Sleeve	2	5.50	1.00	1.00	1.38	1.00	1.00	0.25	1.00	1.00	-2.00	0.00	0.00	2.00	4.00	0.97
14	ABC: D	Intake Seat	2	3.00	3.00	0.50	0.01	0.01	0.01	0.00	0.00	0.02	-8.23	-8.23	-5.64	22.10	44.21	0.70
15	AB:C	Exhaust Seat	2	3.00	3.00	0.50	0.01	0.01	0.01	0.00	0.00	0.02	-8.23	-8.23	-5.64	22.10	44.21	0.70
16	A: B	Plug	1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
17	A	Cylinder head	1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00

Table 62 Accessibility calculations for Series B

S.no	Disassembly Sequence	Part	Qty	X	Y	Z	Δx	Δy	Δz	Δx/X	Δy/Y	Δz/Z	log2 (Δx/X)	log2 (Δy/Y)	log2 (Δz/Z)	Iacc	Iacc*Qty	Iacc Rating
1	ABCDEFGHIJKLMNOPQRST: U	Hex Nut	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
2	ABCDEFGHIJKLMNOPQRS: T	Spark Plug Flange	1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
3	ABCDEFGHIJKLMNOPQR: S	Spark Plug Socket	1	9.50	2.88	2.88	2.00	1.88	1.88	0.21	0.65	0.65	-2.25	-0.62	-0.62	3.48	3.48	0.98
4	ABCDEFGHIJKLMNOPQ: R	O-Ring	1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
5	ABCDEFGHIJKLMNOP: Q	Sealing Ring	1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
6	ABCDEFGHIJKLMNO: P	Keepers	8	0.50	0.88	0.75	0.01	0.01	0.01	0.02	0.01	0.01	-5.64	-6.45	-6.23	18.32	146.59	0.00
7	ABCDEFGHIJKLMN: O	Spring Retainer	4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
8	ABCDEFGHIJKLM: N	E O Spring	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
9	ABCDEFGHIJKL:M	E I Spring	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
10	ABCDEFGHIJK: L	I O Spring	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
11	ABCDEFGHIJ: K	I I Spring	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
12	ABCDEFGHI: J	Washer	4	0.25	0.25	0.13	0.25	0.25	0.10	1.00	1.00	0.80	0.00	0.00	-0.32	0.32	1.29	0.99
13	ABCDEFGH: I	Intake Valve	2	11.00	3.00	3.00	2.50	0.01	0.01	0.23	0.00	0.00	-2.14	-8.23	-8.23	18.60	37.20	0.75
14	ABCDEFG:H	Exhaust Valve	2	11.00	3.00	3.00	2.50	0.01	0.01	0.23	0.00	0.00	-2.14	-8.23	-8.23	18.60	37.20	0.75
15	ABCDEF: G	Valve Guide Seal	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
16	ABCDE: F	Valve Guide Seal	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
17	ABCD: E	Intake Sleeve	2	4.75	1.00	1.00	1.38	1.00	1.00	0.29	1.00	1.00	-1.79	0.00	0.00	1.79	3.58	0.98
18	ABC: D	Exhaust Sleeve	2	5.50	1.00	1.00	1.38	1.00	1.00	0.25	1.00	1.00	-2.00	0.00	0.00	2.00	4.00	0.97
19	AB:C	Intake Seat	2	3.00	3.00	0.50	0.01	0.01	0.01	0.00	0.00	0.02	-8.23	-8.23	-5.64	22.10	44.21	0.70
20	A: B	Exhaust Seat	2	3.00	3.00	0.50	0.01	0.01	0.01	0.00	0.00	0.02	-8.23	-8.23	-5.64	22.10	44.21	0.70
21	A	Cylinder head	1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00

Appendix I: Time Study Data for Series A

Table 63 Time Study of 30 Cores for Series A

Sno.	Disassembly (min)	I&T (min)	Assembly Time (min)	Machining Time (min)	Cleaning (min)	REMAN Time (min)	Reman Time (hrs.)
1	11.3	9.1	26.3	34.5	90.2	171.4	2.9
2	13.1	9.1	18.7	35.6	98.9	175.4	2.9
3	13.5	10.3	29.0	36.0	95.7	184.5	3.1
4	12.1	10.0	27.0	34.6	98.8	182.5	3.0
5	9.8	9.9	23.2	38.1	95.6	176.6	2.9
6	16.7	9.3	27.2	36.7	88.4	178.3	3.0
7	11.0	9.6	22.3	37.4	111.4	191.7	3.2
8	12.0	10.4	30.6	33.9	100.2	187.1	3.1
9	13.3	10.3	22.0	36.2	99.6	181.4	3.0
10	13.6	9.0	21.6	40.8	87.6	172.6	2.9
11	10.2	11.0	22.2	36.6	86.3	166.3	2.8
12	8.5	9.9	21.1	38.0	94.6	172.1	2.9
13	11.4	10.5	35.0	36.3	111.2	204.4	3.4
14	11.7	10.3	28.1	37.8	89.4	177.3	3.0
15	11.3	10.0	27.7	33.4	95.5	177.9	3.0
16	9.5	9.3	23.2	38.0	99.3	179.3	3.0
17	11.2	10.4	30.0	38.4	90.3	180.3	3.0
18	9.6	9.0	9.3	37.2	89.9	155.0	2.6
19	11.2	9.4	2.0	29.3	68.5	120.4	1.9
20	13.4	10.6	25.3	36.8	93.4	179.5	3.0
21	11.8	10.4	26.9	36.4	97.7	183.2	3.1
22	15.4	10.0	2.1	28.8	68.1	124.4	2.0
23	13.1	10.4	21.0	36.8	98.6	179.9	3.0
24	10.2	9.4	21.1	34.2	113.4	188.3	3.1
25	11.1	9.4	31.5	39.4	107.6	199.0	3.3
26	13.3	10.3	26.4	33.4	97.0	180.4	3.0
27	11.9	9.1	29.9	35.1	102.5	188.5	3.1
28	11.6	10.5	22.9	36.1	102.4	183.5	3.1
29	15.2	9.5	26.1	36.4	93.2	180.4	3.0
30	15.4	10.5	2.1	29.7	69.1	126.8	2.0

Appendix J: Time Study Data for Series B

Table 64 Time Study of 30 Cores for Series B

Sno.	Disassembly (min)	I&T (min)	Assembly Time (min)	Machining Time (min)	Cleaning (min)	Reman. Time (min)	Reman Time (hrs.)
1	10.3	11.0	33.4	37.2	117.4	209.3	3.5
2	10.9	10.2	33.2	34.6	124.6	213.5	3.6
3	12.9	10.8	32.6	35.4	107.1	198.8	3.3
4	9.8	10.1	27.7	36.0	118.4	202.0	3.4
5	10.5	10.3	39.3	39.0	101.2	200.3	3.3
6	10.1	10.7	40.1	38.8	109.2	208.9	3.5
7	12.0	10.1	29.3	37.0	115.8	204.2	3.4
8	11.2	10.0	37.8	37.2	99.3	195.5	3.3
9	12.8	10.3	33.4	35.1	103.6	195.2	3.3
10	11.5	10.7	30.0	38.1	109.2	199.5	3.3
11	10.7	10.8	26.0	35.5	103.1	186.1	3.1
12	13.7	10.7	39.3	38.9	111.6	214.2	3.6
13	10.2	10.6	27.3	36.5	106.7	191.3	3.2
14	13.0	10.8	31.1	35.3	103.2	193.4	3.2
15	10.8	10.9	32.1	39.2	106.6	199.6	3.3
16	10.9	10.2	32.0	38.2	111.4	202.7	3.4
17	13.7	10.3	31.3	33.6	111.1	200.0	3.3
18	10.3	10.7	40.8	37.7	120.0	219.5	3.7
19	11.3	10.1	33.4	34.4	109.3	198.5	3.3
20	12.5	10.9	35.7	34.2	90.7	184.0	3.1
21	11.5	10.5	33.1	35.1	107.1	197.3	3.3
22	8.7	10.2	29.4	37.1	115.7	201.1	3.4
23	10.9	10.1	36.4	34.4	115.6	207.4	3.5
24	11.1	5.0	0.0	0.0	75.7	91.8	1.5
25	12.2	10.8	28.8	35.8	100.8	188.4	3.1
26	9.6	10.1	34.8	36.8	102.5	193.8	3.2
27	11.0	10.6	39.4	35.1	90.2	186.3	3.1
28	12.2	10.4	28.7	38.3	97.5	187.1	3.1
29	9.2	10.0	32.1	37.5	95.0	183.8	3.1
30	12.0	10.9	2.1	30.0	84.3	139.3	2.3

Appendix K: ‘q_{DN}’ recordings

Table 65 ‘q_{DN}’ results for Series A

Component	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Cylinder Head	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Intake Valve Sleeve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intake Valve Seal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exhaust Valve Seal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intake Valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exhaust Valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Keeper	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inner Exh. Spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Outer Exh. Spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inner Intake Spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Outer Intake Spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hex Plug	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Exh. Valve Sleeve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Valve Seat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Washer	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Retainer	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 66 ‘q_{DN}’ results for Series B

Component	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Cylinder Head	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Intake Valve Sleeve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exhaust Valve Sleeve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O-ring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Keeper	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exhaust Valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intake Valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exhaust Valve Seal (Green)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intake Valve Seal (Blue)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inner Exhaust Spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Outer Exhaust Spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inner Intake Spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Outer Intake Spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spark Plug Sleeve	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Spark Plug Seal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Spark Plug Flange	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Washer	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Retainer	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Hex Nut	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Valve Seat I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Valve Seat E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix L: ‘q_{RN}’ recordings

Table 67 ‘q_{RN}’ results for Series A

Component	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
VHP 2 Cylinder Head	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Intake Valve Sleeve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intake Valve Seal (Blue)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exhaust Valve Seal (Green)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intake Valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exhaust Valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Keeper	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inner Exhaust Spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Outer Exhaust Spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inner Intake Spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Outer Intake Spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hex Plug	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Exhaust Valve Sleeve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Valve Seat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Washer	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1
Retainer	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 68 ‘q_{RN}’ results for Series B

Component	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
VHP 4 Cylinder Head	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
Intake Valve Sleeve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exhaust Valve Sleeve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O-ring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Keeper	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exhaust Valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intake Valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exhaust Valve Seal (Green)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intake Valve Seal (Blue)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inner Exhaust Spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Outer Exhaust Spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inner Intake Spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Outer Intake Spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spark Plug Sleeve	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
Spark Plug Seal	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1
Spark Plug Flange	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	0	1	1
Washer	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Retainer	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Hex Nut	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
Valve Seat I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Valve Seat E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix M: E_{DA}, E_{DMax} and E_{DMin} results of Series B

Table 69 Actual Effort Scenario for disassembly of Series B

VHP 4		Disassembly Force			Material Handling			Requirement of Tools		Accessibility of Joints		Positioning of tool		Total*BOM
S.no.	Activities	Push/Pull	Inter-surface friction	Mat. Stiffness	Grasping	Weight	Sym./Asym.	Force	Torque	Dimension	Location	Sym	Asym	
1	Remove Stud	0	3	0	2	2	0.8	0	2	1	1	1.2	0	26
2	Remove Screw plug	0	3	0	2	2	0.8	0	2	1	1	1.2	0	26
3	Remove Spark plug sleeve	0	3	0	2	2	0.8	2	0	1	1	2	0	13.8
4	Remove Spark plug socket	3	0	0	2	3.5	0.8	2	0	1	1	2	0	15.3
5	Remove keepers	0.5	0	0	2	2	1.2	3	0	1	1	0	0	42.8
6	Remove Retainers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	8.3
7	Remove Springs O.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
8	Remove Springs I.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
9	Remove Washers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
10	Remove Seals	0	0	3	2	2	0.8	2	0	1	1	2	0	55.2
11	Remove Valve I.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	16.6
12	Remove Valve E.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	16.6
13	Remove Sleeves I.	0.5	0	0	4	2	0.8	3	0	1	1	5	0	34.6
14	Remove Sleeves E.	0.5	0	0	4	2	0.8	3	0	1	1	5	0	34.6
15	Remove I. Seat	0	5	0	2	2	0.8	3	0	1	1	1.2	0	32
16	Remove E. Seat	0	3.5	0	4	2	0.8	3	0	1	1	5	0	40.6
												Total Actual Score		**462**

Table 70 Maximum Effort Scenario for disassembly of Series B

VHP 4		Disassembly Force			Material Handling			Requirement of Tools		Accessibility of Joints		Positioning of tool		Total*BOM
S.no.	Activities	Push/Pull	Inter-surface friction	Mat. Stiffness	Grasping	Weight	Sym/Asym	Force	Torque	Dimension	Location	Sym	Asym	
1	Remove Stud	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
2	Remove Screw plug	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
3	Remove Spark plug sleeve	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	9.5
4	Remove Spark plug socket	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	9.5
5	Remove keepers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
6	Remove Retainers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	8.3
7	Remove Springs O.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
8	Remove Springs I.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
9	Remove Washers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
10	Remove Seals	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	38
11	Remove Valve I.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	16.6
12	Remove Valve E.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	16.6
13	Remove Sleeves I.	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
14	Remove Sleeves E.	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
15	Remove I. Seat	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
16	Remove E. Seat	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
												Total Max. Score		**345**

Table 71 Worst Effort Scenario for disassembly of Series B

VHP 4		Disassembly Force			Material Handling			Requirement of Tools		Accessibility of Joints		Positioning of tool		Total*BOM
S.no.	Activities	Push/Pull	Inter-surface friction	Mat. Stiffness	Grasping	Weight	Sym/Asym	Force	Torque	Dimension	Location	Sym	Asym	
1	Remove Stud	0	0	6.5	4	3	5	3	0	2	2	5	0	61
2	Remove Screw plug	0	0	6.5	4	3	5	3	0	2	2	5	0	61
3	Remove Spark plug sleeve	0	0	6.5	4	3	5	3	0	2	2	5	0	30.5
4	Remove Spark plug socket	0	0	6.5	4	3	5	3	0	2	2	5	0	30.5
5	Remove keepers	0	0	6.5	4	3	5	3	0	2	2	0	0	102
6	Remove Retainers	0	0	6.5	4	3	5	3	0	2	2	0	0	25.5
7	Remove Springs O.	0	0	6.5	4	3	5	3	0	2	2	0	0	102
8	Remove Springs I.	0	0	6.5	4	3	5	3	0	2	2	0	0	102
9	Remove Washers	0	0	6.5	4	3	5	3	0	2	2	0	0	102
10	Remove Seals	0	0	6.5	4	3	5	3	0	2	2	5	0	122
11	Remove Valve I.	0	0	6.5	4	3	5	3	0	2	2	0	0	51
12	Remove Valve E.	0	0	6.5	4	3	5	3	0	2	2	0	0	51
13	Remove Sleeves I.	0	0	6.5	4	3	5	3	0	2	2	5	0	61
14	Remove Sleeves E.	0	0	6.5	4	3	5	3	0	2	2	5	0	61
15	Remove I. Seat	0	0	6.5	4	3	5	3	0	2	2	5	0	61
16	Remove E. Seat	0	0	6.5	4	3	5	3	0	2	2	5	0	61
												Total Min.Score		**1085**

Appendix N: E_{DA}, E_{DMax} and E_{DMin} results of Series A

Table 72 Actual Effort Scenario for disassembly of Series A

VHP 2		Disassembly Force			Material Handling			Requirement of Tools		Accessibility of Joints		Positioning of tool		Total*BOM
S.no.	Activities	Push/Pull	Inter-surface friction	Mat. Stiffness	Grasping	Weight	Sym/Asym	Force	Torque	Dimension	Location	Sym	Asym	
1	Remove Screw plug	0	3	0	2	2	0.8	0	2	1	1	1.2	0	26
2	Remove keepers	0.5	0	0	2	2	1.2	3	0	1	1	0	0	42.8
3	Remove Retainers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	8.3
4	Remove Springs O.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
5	Remove Springs I.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
6	Remove Washers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
7	Remove Seals	0	0	3	2	2	0.8	2	0	1	1	2	0	55.2
8	Remove Valve I.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	16.6
9	Remove Valve E.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	16.6
10	Remove Sleeves I.	0.5	0	0	4	2	0.8	3	0	1	1	5	0	34.6
11	Remove Sleeves E.	0.5	0	0	4	2	0.8	3	0	1	1	5	0	34.6
12	Remove Seat	0	5	0	4	2	0.8	3	0	1	1	5	0	87.2
												Total Actual Score		**421.5**

Table 73 Maximum Effort Scenario for disassembly of Series A

VHP 2		Disassembly Force			Material Handling			Requirement of Tools		Accessibility of Joints		Positioning of tool		Total*BOM
S.no.	Activities	Push/Pull	Inter-surface friction	Mat. Stiffness	Grasping	Weight	Sym/Asym	Force	Torque	Dimension	Location	Sym	Asym	
1	Remove Screw plug	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
2	Remove keepers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
3	Remove Retainers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	8.3
4	Remove Springs O.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
5	Remove Springs I.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
6	Remove Washers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
7	Remove Seals	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	38
8	Remove Valve I.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	16.6
9	Remove Valve E.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	16.6
10	Remove Sleeves I.	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
11	Remove Sleeves E.	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
12	Remove Seat	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	38
												Total Max. Score		**307.3**

Table 74 Minimum Effort Scenario for disassembly of Series A

VHP 2		Disassembly Force			Material Handling			Requirement of Tools		Accessibility of Joints		Positioning of tool		Total*BOM
S.no.	Activities	Push/Pull	Inter-surface friction	Mat. Stiffness	Grasping	Weight	Sym/Asym	Force	Torque	Dimension	Location	Sym	Asym	
1	Remove Screw plug	0	0	6.5	4	3	5	3	0	2	2	5	0	61
2	Remove keepers	0	0	6.5	4	3	5	3	0	2	2	0	0	102
3	Remove Retainers	0	0	6.5	4	3	5	3	0	2	2	0	0	25.5
4	Remove Springs O.	0	0	6.5	4	3	5	3	0	2	2	0	0	102
5	Remove Springs I.	0	0	6.5	4	3	5	3	0	2	2	0	0	102
6	Remove Washers	0	0	6.5	4	3	5	3	0	2	2	0	0	102
7	Remove Seals	0	0	6.5	4	3	5	3	0	2	2	5	0	122
8	Remove Valve I.	0	0	6.5	4	3	5	3	0	2	2	0	0	51
9	Remove Valve E.	0	0	6.5	4	3	5	3	0	2	2	0	0	51
10	Remove Sleeves I.	0	0	6.5	4	3	5	3	0	2	2	5	0	61
11	Remove Sleeves E.	0	0	6.5	4	3	5	3	0	2	2	5	0	61
12	Remove Seat	0	0	6.5	4	3	5	3	0	2	2	5	0	122
												Total Min. Score		**962.5**

Appendix O: E_{RA}, E_{RMax} and E_{RMin} results of Series A

Table 75 Actual Effort Scenario for remanufacturing of Series A

VHP 2		Disassembly Force			Material Handling			Requirement of Tools		Accessibility of Joints		Positioning of tool		Adjusted (Sum*BOM)
S.no.	Activities	Push/Pull	Inter-surface friction	Mat. Stiffness	Grasping	Weight	Sym/Asym	Force	Torque	Dimension	Location	Sym	Asym	
1	Remove Screw plug	0	3	0	2	2	0.8	0	2	1	1	1.2	0	26
2	Remove keepers	0.5	0	0	2	2	1.2	3	0	1	1	0	0	42.8
3	Remove Retainers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	8.3
4	Remove Springs O.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
5	Remove Springs I.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
6	Remove Washers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
7	Remove Seals	0	0	3	2	2	0.8	2	0	1	1	2	0	55.2
8	Remove Valve I.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	16.6
9	Remove Valve E.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	16.6
10	Remove Sleeves I.	0.5	0	0	4	2	0.8	3	0	1	1	5	0	34.6
11	Remove Sleeves E.	0.5	0	0	4	2	0.8	3	0	1	1	5	0	34.6
12	Remove Seat	0	5	0	4	2	0.8	3	0	1	1	5	0	87.2
13	Part Hot Wash	1	0	0	3.5	3	4.4	1	0	1	1	0	0	14.9
14	Part Sand Blasting	3	0	0	3.5	3	4.4	3	0	1.6	2	0	5.5	26
15	Part Buffing/Polishing	3	0	0	3.5	3	4.4	2	0	1.6	2	0	2.5	22
16	Part MPT	1	0	0	3.5	3	4.4	3	0	1.6	2	0	2.5	21
17	I. Sleeves assy	0.5	0	0	2	2	0.8	3	0	1.6	2	5	0	33.8
18	E. Sleeves assy	0.5	0	0	2	2	0.8	3	0	1.6	2	5	0	33.8
19	Block Machining	1	0	0	3.5	3	4.4	0	3	1	1	1.2	0	18.1
20	Part Ultrasonic Cleaning	0.5	0	0	3.5	3	4.4	3	0	1	1	1.2	0	17.6
21	Part spray and blow dry	3	0	0	3.5	3	4.4	2	0	1.6	2	0	2.5	22
22	Seat Assy	5	0	0	3.5	2	0.8	2	0	1	1	0	5.5	83.2
23	Block Machining	1	0	0	3.5	3	4.4	0	3	1	1	5	0	21.9
24	Valve Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
25	Valve Seals Assy	1	0	0	2	2	0.8	2	0	1	1	2	0	47.2
26	Washers installation	0.5	0	0	2	2	0.8	1	0	1	1	0	0	8.3
27	I. Spring Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
28	O. Spring Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
29	Retainer Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
30	Keeper Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
31	Screw plug assy	0	3	0	2	2	0.8	0	2	1	1	1.2	0	26
													Total	**983.3**

Table 76 Minimum Effort Scenario for remanufacturing of Series A

VHP 2		Disassembly Force			Material Handling			Requirement of Tools		Accessibility of Joints		Positioning of tool		Total*BOM
S.no.	Activities	Push/Pull	Inter-surface friction	Mat. Stiffness	Grasping	Weight	Sym/Asym	Force	Torque	Dimension	Location	Sym	Asym	
1	Remove Screw plug	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
2	Remove keepers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
3	Remove Retainers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	8.3
4	Remove Springs O.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
5	Remove Springs I.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
6	Remove Washers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
7	Remove Seals	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	38
8	Remove Valve I.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	16.6
9	Remove Valve E.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	16.6
10	Remove Sleeves I.	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
11	Remove Sleeves E.	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
12	Remove Seat	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	38
13	Part Hot Wash	0.5	0	0	2	2	0.8	1	0	1	1	0	0	8.3
14	Part Sand Blasting	0.5	0	0	2	2	0.8	1	0	1	1	0	1.6	9.9
15	Part Buffing/Polishing	0.5	0	0	2	2	0.8	1	0	1	1	0	1.6	9.9
16	Part MPT	0.5	0	0	2	2	0.8	1	0	1	1	0	1.6	9.9
17	I. Sleeves assy	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
18	E. Sleeves assy	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
19	Block Machining	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	9.5
20	Part Ultrasonic Cleaning	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	9.5
21	Part spray and blow dry	0.5	0	0	2	2	0.8	1	0	1	1	0	1.6	9.9
22	Seat Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	1.6	39.6
23	Block Machining	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	9.5
24	Valve Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
25	Valve Seals Assy	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	38
26	Washers installation	0.5	0	0	2	2	0.8	1	0	1	1	0	0	8.3
27	I. Spring Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
28	O. Spring Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
29	Retainer Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
30	Keeper Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
31	Screw plug assy	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
													Total	**692.6**

Table 77 Maximum Effort Scenario for remanufacturing of Series A

VHP 2		Disassembly Force			Material Handling			Requirement of Tools		Accessibility of Joints		Positioning of tool		Total*BOM
S.no.	Activities	Push/Pull	Inter-surface friction	Mat. Stiffness	Grasping	Weight	Sym/Asym	Force	Torque	Dimension	Location	Sym	Asym	
1	Remove Screw plug	0	0	6.5	4	3	5	3	0	2	2	5	0	61
2	Remove keepers	0	0	6.5	4	3	5	3	0	2	2	0	0	102
3	Remove Retainers	0	0	6.5	4	3	5	3	0	2	2	0	0	25.5
4	Remove Springs O.	0	0	6.5	4	3	5	3	0	2	2	0	0	102
5	Remove Springs I.	0	0	6.5	4	3	5	3	0	2	2	0	0	102
6	Remove Washers	0	0	6.5	4	3	5	3	0	2	2	0	0	102
7	Remove Seals	0	0	6.5	4	3	5	3	0	2	2	5	0	122
8	Remove Valve I.	0	0	6.5	4	3	5	3	0	2	2	0	0	51
9	Remove Valve E.	0	0	6.5	4	3	5	3	0	2	2	0	0	51
10	Remove Sleeves I.	0	0	6.5	4	3	5	3	0	2	2	5	0	61
11	Remove Sleeves E.	0	0	6.5	4	3	5	3	0	2	2	5	0	61
12	Remove Seat	0	0	6.5	4	3	5	3	0	2	2	5	0	122
13	Part Hot Wash	0	0	6.5	4	3	5	3	0	2	2	0	0	25.5
14	Part Sand Blasting	0	0	6.5	4	3	5	3	0	2	2	0	5.5	31
15	Part Buffing/Polishing	0	0	6.5	4	3	5	3	0	2	2	0	5.5	31
16	Part MPT	0	0	6.5	4	3	5	3	0	2	2	0	5.5	31
17	I. Sleeves assy	0	0	6.5	4	3	5	3	0	2	2	5	0	61
18	E. Sleeves assy	0	0	6.5	4	3	5	3	0	2	2	5	0	61
19	Block Machining	0	0	6.5	4	3	5	3	0	2	2	5	0	30.5
20	Part Ultrasonic Cleaning	0	0	6.5	4	3	5	3	0	2	2	5	0	30.5
21	Part spray and blow dry	0	0	6.5	4	3	5	3	0	2	2	0	5.5	31
22	Seat Assy	0	0	6.5	4	3	5	3	0	2	2	0	5.5	124
23	Block Machining	0	0	6.5	4	3	5	3	0	2	2	5	0	30.5
24	Valve Assy	0	0	6.5	4	3	5	3	0	2	2	0	0	102
25	Valve Seals Assy	0	0	6.5	4	3	5	3	0	2	2	5	0	122
26	Washers installation	0	0	6.5	4	3	5	3	0	2	2	0	0	25.5
27	I. Spring Assy	0	0	6.5	4	3	5	3	0	2	2	0	0	102
28	O. Spring Assy	0	0	6.5	4	3	5	3	0	2	2	0	0	102
29	Retainer Assy	0	0	6.5	4	3	5	3	0	2	2	0	0	102
30	Keeper Assy	0	0	6.5	4	3	5	3	0	2	2	0	0	102
31	Screw plug assy	0	0	6.5	4	3	5	3	0	2	2	5	0	61
													Total	2168

Appendix P: E_{RA}, E_{RMax} and E_{RMin} results of Series B

Table 78 Actual Effort Scenario for remanufacturing of Series B

VHP 4		Disassembly Force			Material Handling			Requirement of Tools		Accessibility of Joints		Positioning of tool		Total*BOM
S.no.	Activities	Push/Pull	Inter-surface friction	Mat. Stiffness	Grasping	Weight	Sym/Asym	Force	Torque	Dimension	Location	Sym	Asym	
1	Remove Stud	0	3	0	2	2	0.8	0	2	1	1	1.2	0	26
2	Remove Screw plug	0	3	0	2	2	0.8	0	2	1	1	1.2	0	26
3	Remove Spark plug sleeve	0	3	0	2	2	0.8	2	0	1	1	2	0	13.8
4	Remove Spark plug socket	3	0	0	2	3.5	0.8	2	0	1	1	2	0	15.3
5	Remove keepers	0.5	0	0	2	2	1.2	3	0	1	1	0	0	42.8
6	Remove Retainers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	8.3
7	Remove Springs O.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
8	Remove Springs I.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
9	Remove Washers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
10	Remove Seals	0	0	3	2	2	0.8	2	0	1	1	2	0	55.2
11	Remove Valve I.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	16.6
12	Remove Valve E.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	16.6
13	Remove Sleeves I.	0.5	0	0	4	2	0.8	3	0	1	1	5	0	34.6
14	Remove Sleeves E.	0.5	0	0	4	2	0.8	3	0	1	1	5	0	34.6
15	Remove I. Seat	0	5	0	2	2	0.8	3	0	1	1	1.2	0	32
16	Remove E. Seat	0	3.5	0	4	2	0.8	3	0	1	1	5	0	40.6
17	Part Hot Wash	1	0	0	3.5	3	4.4	1	0	1	1	0	0	14.9
18	Part Sand Blasting	3	0	0	3.5	3	4.4	3	0	1.6	2	0	5.5	26
19	Part Buffing/Polishing	3	0	0	3.5	3	4.4	2	0	1.6	2	0	2.5	22
20	Part MPT	1	0	0	3.5	3	4.4	3	0	1.6	2	0	2.5	21
21	I. Sleeves assy	0.5	0	0	2	2	0.8	3	0	1.6	2	5	0	33.8
22	E. Sleeves assy	0.5	0	0	2	2	0.8	3	0	1.6	2	5	0	33.8
23	Block Machining	1	0	0	3.5	3	4.4	0	3	1	1	1.2	0	18.1
24	Part Ultrasonic Cleaning	0.5	0	0	3.5	3	4.4	3	0	1	1	1.2	0	17.6
25	Part spray and blow dry	3	0	0	3.5	3	4.4	2	0	1.6	2	0	2.5	22
26	Spark Plug Socket assy	0	3.5	0	2	3.5	0.8	2	0	1	1	2	0	15.8
27	Spark Plug Sleeve assy	0.5	0	0	2	2	0.8	2	0	1	1	2	0	11.3
28	Seat Assy	5	0	0	3.5	2	0.8	2	0	1	1	0	5.5	83.2
29	Block Machining	1	0	0	3.5	3	4.4	0	3	1	1	5	0	21.9
30	Valve Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
31	Valve Seals Assy	1	0	0	2	2	0.8	2	0	1	1	2	0	47.2
32	Washers installation	0.5	0	0	2	2	0.8	1	0	1	1	0	0	8.3
33	I. Spring Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
34	O. Spring Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
35	Retainer Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
36	Keeper Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
37	Screw plug assy	0	3	0	2	2	0.8	0	2	1	1	1.2	0	26
38	Stud Assy	0	3	0	2	2	0.8	0	2	1	1	1.2	0	26
													Total	**1076.9**

Table 79 Minimum Effort Scenario for remanufacturing of Series B

VHP 4		Disassembly Force			Material Handling			Requirement of Tools		Accessibility of Joints		Positioning of tool		Total*BOM
S.no.	Activities	Push/Pull	Inter-surface friction	Mat. Stiffness	Grasping	Weight	Sym/Asym	Force	Torque	Dimension	Location	Sym	Asym	
1	Remove Stud	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
2	Remove Screw plug	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
3	Remove Spark plug sleeve	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	9.5
4	Remove Spark plug socket	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	9.5
5	Remove keepers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
6	Remove Retainers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	8.3
7	Remove Springs O.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
8	Remove Springs I.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
9	Remove Washers	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
10	Remove Seals	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	38
11	Remove Valve I.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	16.6
12	Remove Valve E.	0.5	0	0	2	2	0.8	1	0	1	1	0	0	16.6
13	Remove Sleeves I.	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
14	Remove Sleeves E.	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
15	Remove I. Seat	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
16	Remove E. Seat	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
17	Part Hot Wash	0.5	0	0	2	2	0.8	1	0	1	1	0	0	8.3
18	Part Sand Blasting	0.5	0	0	2	2	0.8	1	0	1	1	0	1.6	9.9
19	Part Buffing/Polishing	0.5	0	0	2	2	0.8	1	0	1	1	0	1.6	9.9
20	Part MPT	0.5	0	0	2	2	0.8	1	0	1	1	0	1.6	9.9
21	I. Sleeves assy	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
22	E. Sleeves assy	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
23	Block Machining	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	9.5
24	Part Ultrasonic Cleaning	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	9.5
25	Part spray and blow dry	0.5	0	0	2	2	0.8	1	0	1	1	0	1.6	9.9
26	Spark Plug Socket assy	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	9.5
27	Spark Plug Sleeve assy	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	9.5
28	Seat Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	1.6	39.6
29	Block Machining	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	9.5
30	Valve Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
31	Valve Seals Assy	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	38
32	Washers installation	0.5	0	0	2	2	0.8	1	0	1	1	0	0	8.3
33	I. Spring Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
34	O. Spring Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
35	Retainer Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
36	Keeper Assy	0.5	0	0	2	2	0.8	1	0	1	1	0	0	33.2
37	Screw plug assy	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
38	Stud Assy	0.5	0	0	2	2	0.8	1	0	1	1	1.2	0	19
													Total	**768.6**

Table 80 Maximum Effort Scenario for remanufacturing of Series B

VHP 4		Disassembly Force			Material Handling			Requirement of Tools		Accessibility of Joints		Positioning of tool		Total*BOM
S.no.	Activities	Push/Pull	Inter-surface friction	Mat. Stiffness	Grasping	Weight	Sym/Asym	Force	Torque	Dimension	Location	Sym	Asym	
1	Remove Stud	0	0	6.5	4	3	5	3	0	2	2	5	0	61
2	Remove Screw plug	0	0	6.5	4	3	5	3	0	2	2	5	0	61
3	Remove Spark plug sleeve	0	0	6.5	4	3	5	3	0	2	2	5	0	30.5
4	Remove Spark plug socket	0	0	6.5	4	3	5	3	0	2	2	5	0	30.5
5	Remove keepers	0	0	6.5	4	3	5	3	0	2	2	0	0	102
6	Remove Retainers	0	0	6.5	4	3	5	3	0	2	2	0	0	25.5
7	Remove Springs O.	0	0	6.5	4	3	5	3	0	2	2	0	0	102
8	Remove Springs I.	0	0	6.5	4	3	5	3	0	2	2	0	0	102
9	Remove Washers	0	0	6.5	4	3	5	3	0	2	2	0	0	102
10	Remove Seals	0	0	6.5	4	3	5	3	0	2	2	5	0	122
11	Remove Valve I.	0	0	6.5	4	3	5	3	0	2	2	0	0	51
12	Remove Valve E.	0	0	6.5	4	3	5	3	0	2	2	0	0	51
13	Remove Sleeves I.	0	0	6.5	4	3	5	3	0	2	2	5	0	61
14	Remove Sleeves E.	0	0	6.5	4	3	5	3	0	2	2	5	0	61
15	Remove I. Seat	0	0	6.5	4	3	5	3	0	2	2	5	0	61
16	Remove E. Seat	0	0	6.5	4	3	5	3	0	2	2	5	0	61
17	Part Hot Wash	0	0	6.5	4	3	5	3	0	2	2	0	0	25.5
18	Part Sand Blasting	0	0	6.5	4	3	5	3	0	2	2	0	5.5	31
19	Part Buffing/Polishing	0	0	6.5	4	3	5	3	0	2	2	0	5.5	31
20	Part MPT	0	0	6.5	4	3	5	3	0	2	2	0	5.5	31
21	I. Sleeves assy	0	0	6.5	4	3	5	3	0	2	2	5	0	61
22	E. Sleeves assy	0	0	6.5	4	3	5	3	0	2	2	5	0	61
23	Block Machining	0	0	6.5	4	3	5	3	0	2	2	5	0	30.5
24	Part Ultrasonic Cleaning	0	0	6.5	4	3	5	3	0	2	2	5	0	30.5
25	Part spray and blow dry	0	0	6.5	4	3	5	3	0	2	2	0	5.5	31
26	Spark Plug Socket assy	0	0	6.5	4	3	5	3	0	2	2	5	0	30.5
27	Spark Plug Sleeve assy	0	0	6.5	4	3	5	3	0	2	2	5	0	30.5
28	Seat Assy	0	0	6.5	4	3	5	3	0	2	2	0	5.5	124
29	Block Machining	0	0	6.5	4	3	5	3	0	2	2	5	0	30.5
30	Valve Assy	0	0	6.5	4	3	5	3	0	2	2	0	0	102
31	Valve Seals Assy	0	0	6.5	4	3	5	3	0	2	2	5	0	122
32	Washers installation	0	0	6.5	4	3	5	3	0	2	2	0	0	25.5
33	I. Spring Assy	0	0	6.5	4	3	5	3	0	2	2	0	0	102
34	O. Spring Assy	0	0	6.5	4	3	5	3	0	2	2	0	0	102
35	Retainer Assy	0	0	6.5	4	3	5	3	0	2	2	0	0	102
36	Keeper Assy	0	0	6.5	4	3	5	3	0	2	2	0	0	102
37	Screw plug assy	0	0	6.5	4	3	5	3	0	2	2	5	0	61
38	Stud Assy	0	0	6.5	4	3	5	3	0	2	2	5	0	61
													Total	**2412**

References

Amezquita, T., Hammond, R., Salazar, M., & Bras, B. (1995). Characterizing the Remanufacturability of Engineering Systems. *Proceedings of ASME Advances in Design Automation Conference, DE-Vol. 82, September 17–20*, (1993), 271–278.

Amigó, E., Gonzalo, J., Artiles, J. and Verdejo, F. (2011). Combining evaluation metrics via the unanimous improvement ratio and its application to clustering tasks. *Journal of Artificial Intelligence Research (JAIR), Vol. 42 No*, 689–718.

Aras, N., Boyaci, T., & Verter, V. (2004). The effect of categorizing returned products in remanufacturing. *IIE Transactions*, *36*(4), 319–331. https://doi.org/10.1080/07408170490279561

Armacost, R., Balakrishnan, D., & Pet-Armacost, J. (2002). Design for Remanufacturability Using QFD, (May), 1–5. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.19.6175&rep=rep1&type=pdf

Aydin, R., Brown, A., Ali, A., & Badurdeen, F. (2017). Assessment of end-of-life product lifecycle "ilities." In *67th Annual Conference and Expo of the Institute of Industrial Engineers 2017* (pp. 1691–1696). Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85031032189&partnerID=40&md5=7e8aa3e99f68841bdb39c0abdb2f6cf3

Bao, H. P., Uppuluri, S., Anityasari, M., & Manmek, S. (2006). A strategy for product reuse in support of life-cycle engineering. *International Journal of Agile Manufacturing*, *9*(2), 3–12.

Bhattacharya, R., & Kaur, A. (2015). Allocation of external returns of different quality grades to multiple stages of a closed loop supply chain. *Journal of Manufacturing Systems*, 1–11. https://doi.org/10.1016/j.jmsy.2015.01.004

Bras, B., & Hammond, R. (1996). Towards Design for Remanufacturing – Metrics for Assessing Remanufacturability. *Proceedings of the 1st International Workshop on Reuse*, 5–22.

Das, S., & Naik, S. (2002). Process planning for product disassembly. *International Journal of Production Research*, *40*(6), 1335–1355. https://doi.org/10.1080/00207540110102142

Desai, A., & Mital, A. (2003). Evaluation of disassemblability to enable design for disassembly in mass production. *International Journal of Industrial Ergonomics*, *32*(4), 265–281. https://doi.org/10.1016/S0169-8141(03)00067-2

Dictionary.com. (2016). Dictionary. Retrieved from http://www.dictionary.com/browse/-ility

EPA. (2017). Reduce, Reuse, Recycle. Retrieved August 17, 2017, from https://www.epa.gov/recycle

Fang, H. C., Ong, S. K., & Nee, A. Y. C. (2015). Product remanufacturability assessment and implementation based on design features. *Procedia CIRP*, *26*, 571–576. https://doi.org/10.1016/j.procir.2014.07.027

Fang, H. C., Ong, S. K., & Nee, A. Y. C. (2016). An Integrated Approach for Product Remanufacturing Assessment and Planning. *Procedia CIRP*, *40*, 262–267. https://doi.org/10.1016/j.procir.2016.01.118

Feng, L., Zhang, J., & Tang, W. (2013). Optimal control of production and remanufacturing for a recovery system with perishable items. *International Journal of Production Research*, *51*(13), 3977–3994. https://doi.org/10.1080/00207543.2012.762133

Ferguson, M. (2009). The Value of Quality Grading in Remanufacturing, *18*(3), 300–314.

Fujimoto, H., Ahmed, A., & Sugi, K. (2001). Product's disassemblability evaluation using Information Entropy. *Electronics*, 353–359. https://doi.org/10.1109/ECODIM.2001.992380

Gadh, R., Srinivasan, H., Nuggehalli, S., & Figueroa, R. (1998). Virtual disassembly-a software tool for developing product\ndismantling and maintenance systems. *Annual Reliability and Maintainability Symposium. 1998 Proceedings. International Symposium on Product Quality and Integrity*, 120–125.

Giudice, F., & Kassem, M. (2009). End-of-life impact reduction through analysis and redistribution of disassembly depth: A case study in electronic device redesign. *Computers and Industrial Engineering*, *57*(3), 677–690. https://doi.org/10.1016/j.cie.2009.01.007

Gray, R. M. (2011). Entropy and Information Theory. *Springer*.

Gungor, A., & Gupta, S. M. (1999). Issues in environmentally conscious manufacturing and product recovery: A survey. *Computers and Industrial Engineering*, *36*(4), 811–853. https://doi.org/10.1016/S0360-8352(99)00167-9

Ijomah, W. L., McMahon, C. a., Hammond, G. P., & Newman, S. T. (2007). Development of robust design-for-remanufacturing guidelines to further the aims of sustainable development. *International Journal of Production Research*, *45*(18–19), 4513–4536. https://doi.org/10.1080/00207540701450138

ISM. (2017). *6R Methodology - Revised Definitions*. Lexington. Retrieved from https://www.engr.uky.edu/ism/

Johnson, M. R., & Wang, M. H. (1998). Economical evaluation of disassembly operations for recycling, remanufacturing and reuse. *International Journal of Production Research*, *36*(12), 3227–3252. https://doi.org/10.1080/002075498192049

Kaebernick, H. and Anityasari, M. (2008). A concept of reliability evaluation for reuse and remanufacturing Maria Anityasari * and Hartmut Kaebernick. *Int. Journal Sustainable Manufacturing*, *1*, 3–17. https://doi.org/10.1504/IJSM.2008.019224

Kaebernick, H., Kara, S., & Sun, M. (2003). Sustainable product development and manufacturing by considering environmental requirements. *Robotics and Computer-Integrated Manufacturing*, *19*(6), 461–468. https://doi.org/10.1016/S0736-5845(03)00056-5

Kim, T., & Goyal, S. K. (2011). Determination of the optimal production policy and product recovery policy: The impacts of sales margin of recovered product. *International Journal of Production Research*, *49*(9), 2535–2550. https://doi.org/10.1080/00207543.2010.532918

Kroll, E., & Carver, B. S. (1999). Disassembly analysis through time estimation and other metrics. *Robotics and Computer-Integrated Manufacturing*, *15*(3), 191–200. https://doi.org/10.1016/S0736-5845(99)00026-5

Kwak, M., & Kim, H. M. (2010). Evaluating End-of-Life Recovery Profit by a Simultaneous Consideration of Product Design and Recovery Network Design. *Journal of Mechanical Design*, *132*(7), 71001. https://doi.org/10.1115/1.4001411

Lebreton, B., & Tuma, A. (2006). A quantitative approach to assessing the profitability of car and truck tire remanufacturing. *International Journal of Production Economics*, *104*(2), 639–652. https://doi.org/10.1016/j.ijpe.2004.11.010

Lu, B., Li, B., Wang, L., Yang, J., Liu, J., & Wang, X. V. (2014). Reusability based on life cycle sustainability assessment: Case study on WEEE. *Procedia CIRP*, *15*, 473–478. https://doi.org/10.1016/j.procir.2014.06.046

Lu, T., & Jawahir, I. S. (2015). Metrics-based Sustainability Evaluation of Cryogenic Machining. *Procedia CIRP*, *29*, 520–525. https://doi.org/10.1016/j.procir.2015.02.067

Mabee, D. G., Bommer, M., & Keat, W. D. (1999). Design charts for remanufacturing assessment. *Journal of Manufacturing Systems*, *18*(5), 358–366. https://doi.org/10.1016/S0278-6125(00)87638-4

Mangun, D., & Thurston, D. L. (2002). Incorporating component reuse, remanufacture, and recycle into product portfolio design. *IEEE Transactions on Engineering Management*, *49*(4), 479–

490. https://doi.org/10.1109/TEM.2002.807292

Paul, R. P. (1981). Robot Manipulators: Mathematics, Programming, and Control. In *MIT Press*.

Polotski, V., Kenne, J. P., & Gharbi, A. (2015). Optimal production scheduling for hybrid manufacturing-remanufacturing systems with setups. *Journal of Manufacturing Systems*, *37*, 703–714. https://doi.org/10.1016/j.jmsy.2015.02.001

Priyono, A., Ijomah, W., & Bititci, U. (2016). Disassembly for remanufacturing: A systematic literature review, new model development and future research needs. *Journal of Industrial Engineering and Management*, *9*(4), 899. https://doi.org/10.3926/jiem.2053

Reimer, B., Sodhi, M. S., & Knight, W. A. (2000). Optimizing electronics end-of-life disposal costs. *IEEE International Symposium on Electronics and the Environment*, 342–347. https://doi.org/10.1109/ISEE.2000.857672

Robotis, A., Boyaci, T., & Verter, V. (2012). Investing in reusability of products of uncertain remanufacturing cost: The role of inspection capabilities. *International Journal of Production Economics*, *140*(1), 385–395. https://doi.org/10.1016/j.ijpe.2012.04.017

Shu, L. H., & Flowers, W. C. (1999). Application of a design-for-remanufacture framework to the selection of product life-cycle fastening and joining methods. *Robotics and Computer-Integrated Manufacturing*, *15*(3), 179–190. https://doi.org/10.1016/S0736-5845(98)00032-5

Sodhi, M., & Knight, W. A. (1998). Product Design for Disassembly and Bulk Recycling. *CIRP Annals - Manufacturing Technology*, *47*(1), 115–118. https://doi.org/10.1016/S0007-8506(07)62798-X

Sodhi, M. S., & Reimer, B. (2001). Models for recycling electronics end-of-life products. *OR Spektrum*, *23*(February 2001), 97–115. https://doi.org/10.1007/PL00013347

Soh, S., Ong, S. K., Nee, A. Y. C., & Soh, S. L. (2015). Design for assembly and disassembly for remanufacturing. *Assembly Automation*, *36*(1), 12–24. https://doi.org/10.1108/AA-05-2015-040

SRC. (2017). SRC of Lexington. Retrieved from http://www.srclexington.com/

Suga, T., Saneshige, K., & Fujimoto, J. (1996). Quantitative disassembly evaluation. *Proceedings of the 1996 IEEE International Symposium on Electronics and the Environment. ISEE-1996*, 19–24. https://doi.org/10.1109/ISEE.1996.500390

Suh, N. P. (1990). The Principles of Design, Oxford,. In *Oxford University Press* (p. 147–188.).

New York, United States: Oxford University Press; 1 edition (February 1, 1990).

Sundin, E., & Bras, B. (2005). Making functional sales environmentally and economically beneficial through product remanufacturing. *Journal of Cleaner Production*, *13*(9), 913–925. https://doi.org/10.1016/j.jclepro.2004.04.006

Terpenny, J. (2015). *Advance Manufacturing Enterprise*. Retrieved from http://www.uilabs.org/wp-content/uploads/2017/02/AdvanceManufacturingEnterprise.pdf

Tian, G., Qiang, T., Chu, J., Xu, G., & Zhou, W. (2013). Efficiency optimization for disassembly tools via using NN-GA approach. *Mathematical Problems in Engineering*, *2013*. https://doi.org/10.1155/2013/173736

Umeda, Y., Fukushige, S., Mizuno, T., & Matsuyama, Y. (2013). Generating design alternatives for increasing recyclability of products. *CIRP Annals - Manufacturing Technology*, *62*(1), 135–138. https://doi.org/10.1016/j.cirp.2013.03.060

UNEP. (2017). Benefits of Life Cycle Approaches. Retrieved from http://www.lifecycleinitiative.org/starting-life-cycle-thinking/benefits/

Wang, L. L., Zhang, Z. M., & Chen, C. (2012). Evaluation Model for Product Green Design Based on Active Remanufacturing. *Applied Mechanics and Materials, 215–216,* 583–587. https://doi.org/10.4028/www.scientific.net/AMM.215-216.583

Yao, J., Cui, P., Wang, X., & Shi, X. (2014). Product Material Design Assessment Methods for Remanufacturing. *2014 Sixth International Conference on Measuring Technology and Mechatronics Automation*, 459–462. https://doi.org/10.1109/ICMTMA.2014.113

Zhang, X., Badurdeen, F., K., R., & Jawahir, I. S. (2013). On improving the product sustainability of metallic automotive components by using the total life-cycle approach and the 6R methodology, (11th Global Conference on Sustainable Manufacturing-Innovative Solutions), 194–199.

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Publications

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· Ali, A. and Badurdeen, F., “Enhancement Product of End-of-life Recovery options using Quantitative Assessment of Disassemblability”. Pending submission to the Journal of Remanufacturing, Springer.

· Ali, A. and Badurdeen, F., “Enhancement of Product Remanufacturing strategy using Quantitative Assessment of Remanufacturability”. Pending submission to the Journal of Remanufacturing, Springer.