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Insights into the Importance and Challenges of the Cleaning Operation in Automotive Remanufacturing

by

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This thesis is submitted in fulfilment of the requirements of the degree of Master of Philosophy

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ABSTRACT

The common practice of a throw-away life style with only a forward-loop supply chain is causing many issues such as rapid depletion of natural resources, ever-increasing global warming and solid waste issues. The concept of sustainable manufacturing encourages the recovery of used products by promoting closed loop supply chains. Remanufacturing is one such product reuse strategy among other options like repair, recondition and recycle. Remanufacturing returns used products to original performance with a warranty matching a new counterpart. To be price competitive in the market, remanufactured products have to be produced with strict cost control. The cleaning process has been found to be the second most costly operation during remanufacture. This research aims to identify the significance and challenges of cleaning operation in automotive remanufacturing and thereby provide insights to reduce overall cost/effort of remanufacturing. Its main objective is to uncover the factors causing higher cleaning efforts. The research follows an inductive methodology with multiple case study approach. Three remanufacturers (Independent, Contract and OEM) in the automotive sector and one photocopier remanufacturer in the UK were studied. The remanufacturing processes from gate-to-gate were observed and key personnel were interviewed in gathering data. The research was guided by four research questions. Seven factors affecting higher efforts of cleaning were identified. These are, complexity of components in terms of shape and size, type of material being used, environment regulation on waste disposal, excessive debris, corrosion, form of output in the market and approaches for cleaning. These factors are categorised in two dimensions as the 'Technical nature of products and processes' and the 'Business nature of the remanufacturer'. Design for Cleaning (DfC), material selection, use of compound material products and design to last long have been identified as new knowledge areas that could be used in reducing the effort of cleaning. It can be concluded that the new knowledge can be used for both in product design and cleaning equipment design. The research provides a good foundation for a PhD research with a more detailed and in-depth analysis to enhance the profitability of remanufacturing.

1 INTRODUCTION

This chapter presents a background of sustainable manufacturing and introduces remanufacturing in the context. It then presents key end-of-use strategies and explains remanufacturing process steps in detail. The chapter concludes with presenting aim and objectives of the research with an outline for the thesis.

1.1 Background

Since the industrial revolution, society has moved with manufacture, consumption and a throw-away life style where the forward supply chain was prominent. This is where the products are manufactured from virgin raw materials which were extracted from natural resources. These products were used, consuming further energy which is again generated from natural sources like fossils. The used products were then discarded / disposed of causing further damage to the environment by following a cradle-to-grave life cycle. There are two main reasons for products to go out of use or be discarded by users. They are either functional obsolescence where one, or more functions of a product physically fails to operate, or fashion obsolescence where a product loses its popularity/appeal due to introduction of new models to the market with additional/sophisticated features (King et al., 2006). A similar concept has been discussed as Physical life time (PLT) and Value life time (VLT) by Umeda et al., (2007) in their study on life cycle option selection.

This practice still continues, but social concern and awareness over environmental impact of this production and consumption are ever increasing, hence sustainability of this life style is extensively questioned. Rapid depletion of natural resources, ever-increasing global warming and the consequences of disposal of used products drove mankind towards a sustainable way of manufacturing.

According to King et al., (2006) there are only two possible destinies of waste material namely reuse (closed loop) or dissipative loss (open loop) which is a straightforward implication of the law of conservation of mass. Figure 1 illustrates the processes associated with forward supply chain and reverse supply chain. The conventional forward supply consists of the design of products from raw material, mostly from virgin material, and the manufacture of those and their distribution globally to the end consumer. Then comes the used phase where the end consumer uses the product and the majority of the products are disposed as solid waste in landfill sites at the end of life or end of use. This practice creates many environmental and health issues and is restricted by legislation in most countries.

Figure 1: Illustration of forward and reverse supply chains

At the end of use there comes the opportunity of reusing the product in any of the four (4) ways illustrated in Figure 1, namely Repair, Recondition, Remanufacture or Recycle. The processes and activities of returning used products to use again could be referred to as reverse supply chain. Reverse supply chains are introduced to recover the products which are there at the market/customers' end back to the manufacturers' or distributers' end. The motivation for product take back is due to a number of reasons, varying from the profit motive to pressure from legislation (Gehin et al., 2009) and environmental pressure groups. This issue could be addressed in another dimension by incorporating environmental qualities in product design as discussed by (Sakao, 2007).

The concern over climate change and related environmental issues has generated a surge of interest and action towards sustainable development (Nasr et al., 2011). Sustainable development is defined as "*meeting the needs of the present without compromising the ability of future generations to meet their own needs*" (The World Commission on Environment and Development, 1989). Within this domain, sustainable manufacturing is defined as "*Creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound*"(U.S. Department of Commerce, 2013).

To keep the manufacturing system sustainable it is required to power up the reverse supply chain by establishing sustainable product life cycles (Umeda, 2001) which will then reduce the burden on the environment by reducing virgin material extraction, global warming potential and other environmental consequences. However, product reuse is not as easy as expected with traditional product life cycles. Remanufacturing is a preferred way of keeping the product in a closed-loop cycle with less economic and environmental burden (Cunha et al., 2011).

Being one of the main reuse strategies, it is vital to improve the profitability and efficiency of the remanufacturing process. So it is also vital to identify costly or more effortful operations within remanufacturing. From the literature, it was found that the cost of cleaning is only second to new part replacement during automotive remanufacturing (Hammond et al., 1998). Hence the focus of the research is narrowed down to study the cleaning operation of remanufacture (Figure 2). The research will try to understand the cleaning process, its significance, difficulties encountered which make it costly, and any knowledge that could be used to reduce the cost of cleaning.

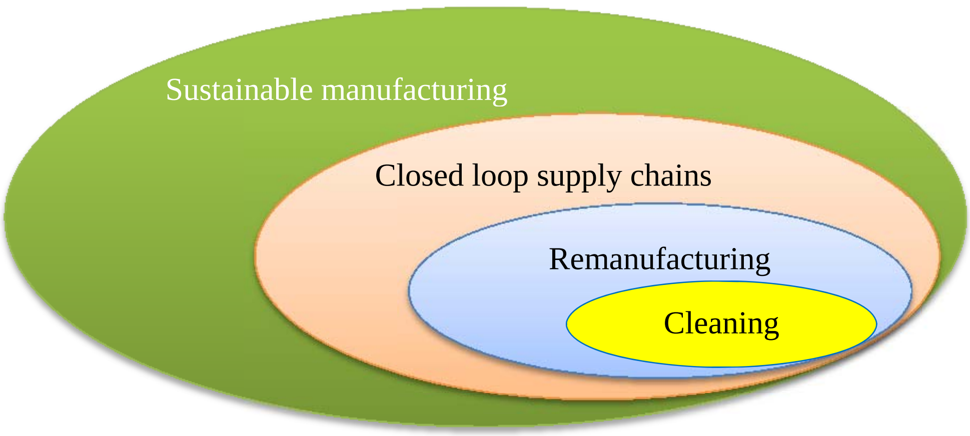


Figure 2: Narrowing down the focus of research to 'Cleaning'

1.2 What is remanufacturing?

Remanufacturing is quite an old concept for high-value products and the term 'remanufacturing' has been used in literature with various definitions but with similar interpretations. Lund, (1983) in his book on the experiences of United States' remanufacturing industry comprehensively defines remanufacturing as "an industrial process in which worn-out products are restored to **like-new** condition. Through a series of industrial processes in a factory environment, a discarded product is completely disassembled. Useable parts are cleaned, refurbished, and put into inventory. Then the new product is reassembled from the old and, where necessary, new parts to produce a fully equivalent and sometimes superior in performance and expected lifetime to the original new product''. A recent publication by Pialot et al., (2012) interprets remanufacturing as "a process which allows decreasing and rationalising the quantities of materials used by recuperating parts of products at the end of the use phase, subjecting them to renewal treatments and then inserting them into new products, therefore prolonging their exploitation (over the long term)" which is a slightly different but an interesting interpretation.

Figure 3 represents the life cycle of a product with available end-of-use options. It clearly denotes the level of warranty/assurance expected with each option, where remanufacturing is at the top. None of the options offers an equivalent or better warranty other than remanufacturing. So it is worthwhile understanding where remanufacturing is among other end-of-use options.

It is essential to distinguish between each end-of-use processes by clarifying the differences to avoid confusion. Often remanufacturing is confused with repair and recondition. The following sections will discuss the definitions of each of these processes and those terms will be frequently used throughout the report.

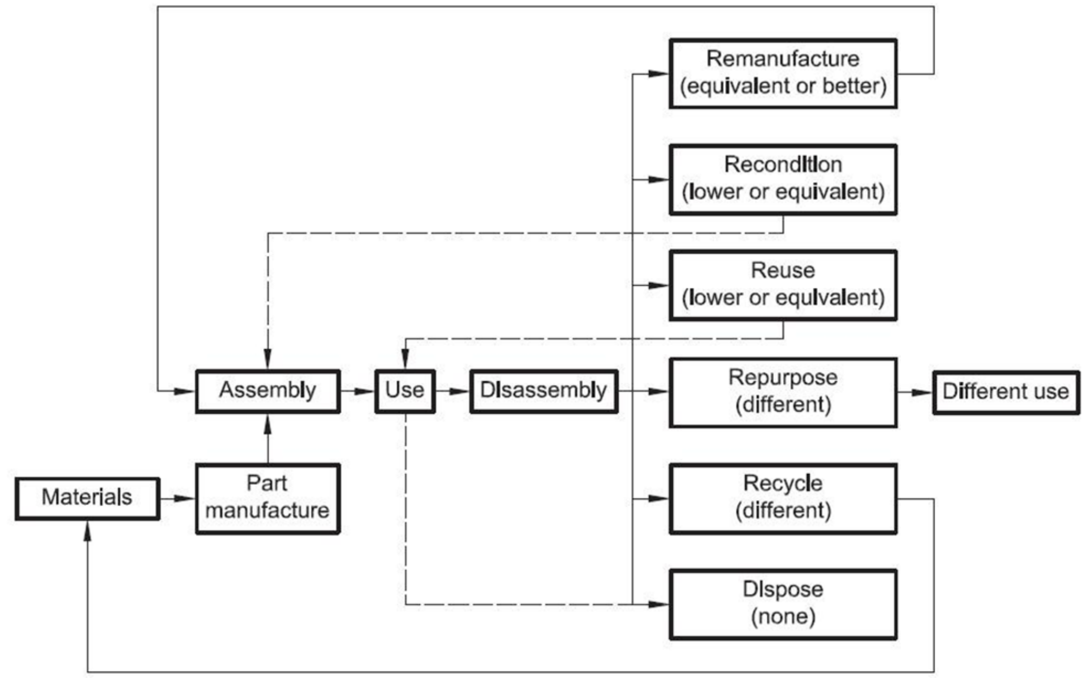


Figure 3: Product life cycle with end-of-use options (British Standards Institute, 2009)

1.2.1 Repair

This term is extensively used with most manufactured products in almost every industry, apart from the products that are designed for single use and consumable goods. For example, fixing the faulty timing belt in an automobile can be considered as repairing. This may involve replacing of reconditioned, remanufactured or brand new parts. This is the fastest or easiest method of returning a malfunctioning product back to usable condition. The term repair is referred to as 'returning a faulty or broken product or component back to a usable state' (British Standards Institute, 2009). The assurance for performance is generally limited for the repaired part. Any warranty applicable for a repaired product is generally less than that for a remanufactured or reconditioned product (British Standards Institute, 2009; Ijomah et al., 2005).

1.2.2 Recondition

Recondition is a common practice especially in the automobile sector where vehicles which have been in use for a couple of years are reconditioned and sold in a different market segment. For example used vehicles in Japan are being reconditioned and sold in developing countries like Sri Lanka where the majority could not afford a brand new product.

Recondition is referred to as "return a used product to a satisfactory working condition by rebuilding or repairing major components that are close to failure, even where there are no reported or apparent faults in those components" (British Standards Institute, 2009). The manufacturing efforts related to replacing worn parts are generally higher than repair but less than remanufacture. The performance of the product after recondition is likely to be less compared with the original product or remanufactured product however better than repaired ones. The warranty is generally less than that of a new counterpart or remanufactured product. However the warranty is likely to cover the entire product rather individual parts like in repair (British Standards Institute, 2009).

1.2.3 Remanufacture

Literature has a variety of definitions for remanufacturing. Hammond et al., (1998) defines remanufacturing as "the practice of disassembling, cleaning, refurbishing, replacing parts (as necessary) and reassembling a product in such a manner that the part is at least as good as, or better than, new".

Remanufacturing is a process of returning a used product to at least the original equipment manufacturers' (OEM) performance specification from the customers' perspective and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent" (Ijomah, 2002). British Standards Institute's standard **BS 8887-2** Design for manufacture, assembly, disassembly and end-of-life processing (MADE) Part 2: Terms and definitions, defines remanufacturing as 'returning a used product to at least its original performance with a warranty that is equivalent to or better than that of the newly manufactured product'(British

Standards Institute, 2009). Both of these will be used as working definitions in this thesis.

Manufacturing effort is higher than that required for recondition or repair as it involves disassembly of the product, restoration and replacement of parts with testing at individual part level and full assembly level. This ensures the remanufactured product meets the original product design specifications which make it equivalent to a new product from the customers' point of view. An equivalent or better performance is expected from a remanufactured product (British Standards Institute, 2009; Ijomah et al., 2005). A more detailed discussion on how remanufacturing is being done is presented in section 1.2.7 below.

1.2.4 Repurpose

Repurpose is "utilisation of a product or its components in a role that it was not originally designed to perform"(British Standards Institute, 2009). In the context of end of life products, it is the use of discarded products or their parts for a purpose other than their initial/original intended purpose. This should not be confused with material recycling to use for other purposes. Here the product or part as a whole unit is being used. For example in the Eden project, used discarded printed circuit boards are being used to manufacture key rings, clip pads, notepads etc (Figure 4).

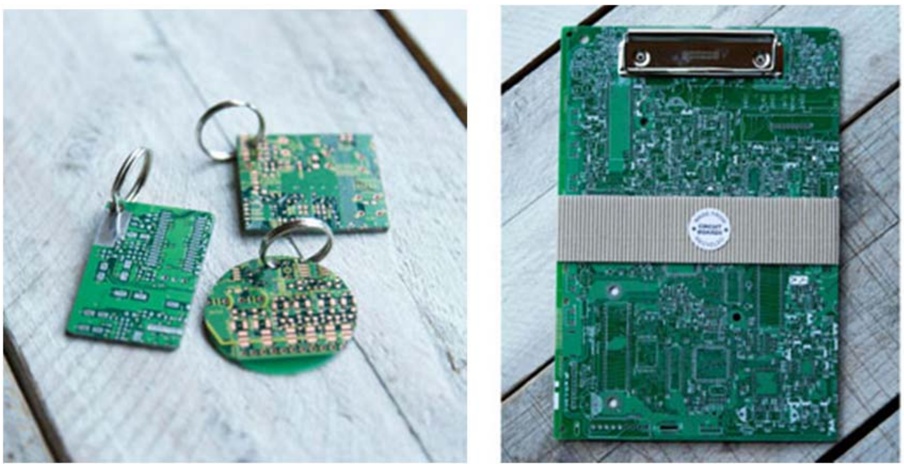


Figure 4: Circuit boards repurpose ("www.edenproject.com," 2013)

1.2.5 Recycle

Recycling is a well-known and established end-of-use strategy which caters for a wide range of products unlike remanufacturing. Discarded or waste products or materials are sorted and processed to recover material to be used in same product manufacture or any other purpose (British Standards Institute, 2009; Ijomah, 2010). Stahel, (1994) defines recycling as series of activities for collecting, sorting and processing discarded materials for use within new products. The main feature is the product loses its original form as recycling is being done at material level, unlike in recondition or remanufacture. It requires a greater amount of effort and energy to sort and process the material.

1.2.6 Summary of end-of-use strategies

In summary the three main reuse strategies can be compared as shown in Figure 5. The diagram is adopted from the PhD thesis titled ‘A Model-based Definition of the Generic Remanufacturing Business Process’ Figure 7.1: “The author's hierarchy of secondary market production processes” (Ijomah, 2002). It positions remanufacture, recondition and repair based on three parameters, performance, work content and warranty. Performance refers to product performance after each strategy and work content refers to the effort required for recovery process. It is evident from the diagram that all three parameters, the performance, work content and warranty are higher for remanufacture compared to recondition and repair. The diagram is presented in way of three equilateral triangles which implies a linear or constant advancement of each parameter which is highly unlikely. This diagram is modified and presented in the Results section considering the non-linear nature of these parameters in the context of automotive industry.

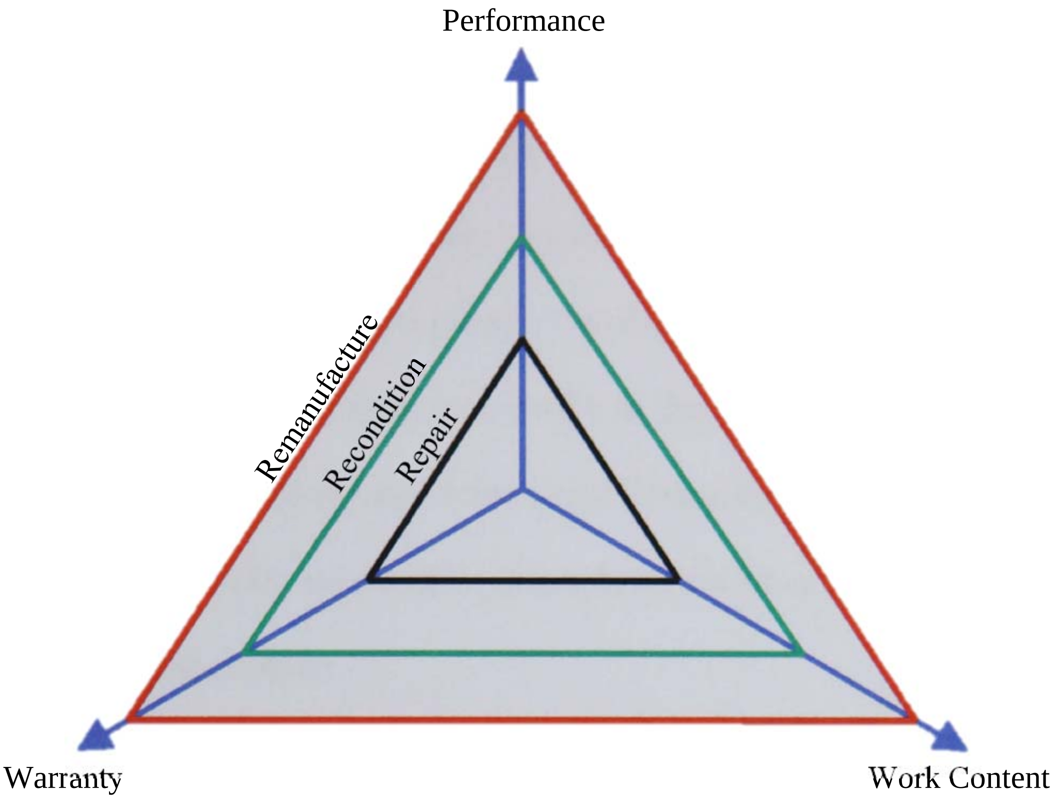


Figure 5:Comparison of repair, recondition and remanufacture(Ijomah, 2002)

1.2.7 Steps in the remanufacturing process

Remanufacturing follows a series of steps when restoring something to the original performance level in an environment similar to manufacturing. Some special tools, jigs and fixtures may be used but the amount of automation is significantly less, compared to a fast-moving manufacturing process. The basic steps involved with a generic remanufacturing process can be illustrated as in Figure 6. These steps can be varied in different degrees depending on the product under remanufacture.

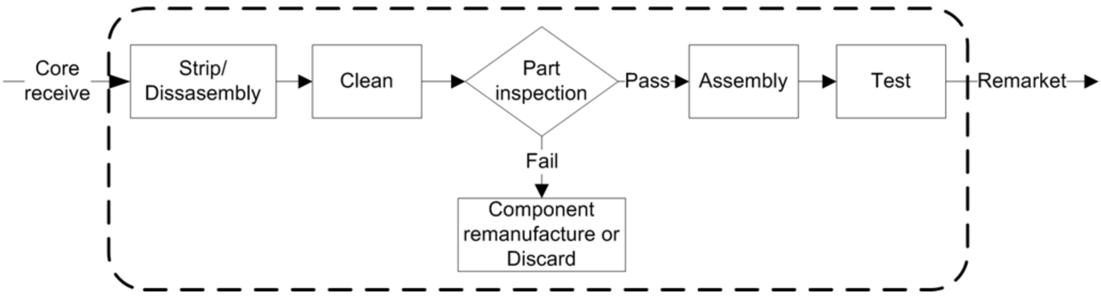


Figure 6 : Basic remanufacturing process (Gamage et al., 2013)

1.2.7.1 Core receipt

The end-of-use products, commonly called ‘Core’ or product ‘Carcasses’, are the main input of the remanufacturing process. This could be considered as the first step in initiating the remanufacturing process. Depending on the type of remanufacturer, the core sourcing may be varied. For example, for an OEM remanufacturer, cores will be received from a business level or individual customers with a certain degree of uncertainty. Contract remanufacturers will normally receive cores in batches with similar models of product to work with which makes the resource planning a little easier. For independent remanufacturers, cores will be received from individual customers or small business units (e.g. vehicle dealerships in automotive remanufacturing) creating greater uncertainty with supply.

1.2.7.2 Disassembly

The second most important step is disassembly or stripping of the received core. Mostly, disassembly is done manually by experienced workers with the use of custom-made tools, jigs and fixtures. The objective disassembly is to strip the product into parts to a level which is sufficient to facilitate the cleaning and subsequent processes. As some subassemblies (e.g. spark plugs, bearing units, electronic controller units, etc.) are replaced as a single unit those are directly reused or scrapped. The disassembled parts are then sorted and stored in containers to be sent to the cleaning process. Some parts, like bearings, oil seals, gaskets, etc., are scraped at the point of disassembly itself as they are going to be replaced irrespective of the condition.

In the automotive remanufacturing industry, custom-made hydraulic pullers to pull-out gears from shafts, custom made carrier trays to accommodate parts of each product model and work stations designed to facilitate efficient disassembly, can be seen. Some researchers have investigated the potential of active disassembly and design for active disassembly (Chiodo and Ijomah, 2012) to facilitate non-destructive disassembly at the end of life. However, in the automotive sector, a major proportion of disassembly is still being done manually, sometimes with destructive methods, depending on the joining techniques involved and as yet there is no significant technological improvement being done in relation to products that are designed for disassembly.

1.2.7.3 Cleaning

The third step in the process of remanufacturing is cleaning. This is where the disassembled parts are cleaned using a variety of methods. The main purpose of cleaning is to facilitate effective inspection of the parts under remanufacturing for detection of any defects or impairments. There are many other reasons for cleaning, such as giving a like-new condition to parts and to improve impaired functional performance. These reasons are discussed in detail in the later part of the thesis under the results and discussion sections. The process utilises both manual and machine aided methods. In the automotive industry, machines like shot blasters and solvent-based agitators are being used to clean certain parts and these are discussed in detail in the case study section.

1.2.7.4 Inspection

Inspection could be considered as the most important step in remanufacturing. This is due to the amount of intellectual input and the skills required in determining the quality of a part. The inspection process is normally carried out by an experienced worker using a minimum of supporting equipment but mainly by visual inspection. For example, in automotive remanufacturing gear wheels and cams are checked for wear and tear, shafts are checked for torsional or bending failures/distortions. Inspection instruments, like surface gauges and magnifying glasses, are being used dependent on the product type. The inspection is supposed to be done according to the OEM’s specification.

Parts are mainly categorised into three main groups namely, good-quality parts which can be directly reused during remanufacture, parts which can be reused after minor/ feasible treatment like grinding, polishing, etc., and parts which are beyond repair or not worthy of repair. The parts beyond repair are usually scrapped or sent for recycling. The scrapped parts are replaced with new or remanufactured parts. Essential replacement parts like bearings, oil rings and gaskets are replaced irrespective of their condition. New parts may be bought from the OEM, OEM approved third party suppliers or a complete substitute product depending on the business strategy of the remanufacturer.

1.2.7.5 Re-assembly

The cleaned and inspected parts, with new replacements parts, are assembled together to make the like-new condition product. General assembly tools and techniques used in the forward manufacturing process are used for this re-assembly process. However, automation still seems difficult to apply as most of the time remanufacturers have to deal with a variety of product types and models within a short time span. Therefore the process is again labour intensive with flexible supportive tools which help to maintain low setting-up time. The assembly process is done referring to the OEM’s product design architecture, to ensure the required performance level is met.

1.2.7.6 Testing

This is the final stage of the remanufacturing process where the assembled product is subjected to a performance test which is similar to the one performed for a newly manufactured product. For example, remanufactured automotive gear boxes are tested for no-load and loaded condition for each gear and for specified RPM levels. It is interesting to see that in automatic transmissions the remanufactured valve bodies are tested for built up oil pressure versus each gear position matching with the OEM specified performance curve. Use of high-tech machinery is evident in the testing stage, compared to the other stages of remanufacturing. If the product failed the test then it is sent back to disassembly for reprocessing, which is highly unlikely.

Figure 7: An automatic transmission testing unit ("www.bluereachautomation.com," 2013)

1.2.8 Types of remanufacturers

There are three main types of remanufacturers in the industry. These varieties of business models are formed on the basis of how they source cores, which market segments they are catering for etc. These are namely, Independent remanufacturers, Contract remanufacturers and OEM remanufacturers.

1.2.8.1 Independent remanufacturers

Independent remanufacturers are typically SMEs. They source aftermarket products through vehicle dealerships, individual customers but hardly from OEMs. This makes for greater uncertainty in core supply with no guarantee of core supply for full-volume operation. They cater for a wider range of product types and brands unlike other types of remanufactures. They have to keep a minimum amount of stock in terms of new and remanufactured spare parts and also remanufactured finished goods. This can be explained with their business model, mostly based on make-to-order rather than make-to-stock. Since the operation is quite simple, they may offer quick and customer-friendly service but with a lower turnaround. One more common thing with independent remanufacturers is that they undertake once-in-life type projects for rare and old-fashioned product models. New parts sourcing is done with trustworthy suppliers selected solely based on the discretion of the company and does not require approval from OEM. Independent remanufacturers source new parts from relatively cheap but trustworthy suppliers to be price competitive with OEM remanufacturers(Ridley, 2012). The source may depend on the criticality of parts being replaced for the whole product performance. In an automobile context, a discarded valve body of an automatic transmission may better be sourced from the OEM rather than a cheap substitute, considering the criticality of the part.

1.2.8.2 Contract remanufacturers

Contract remanufacturers are under contract with an OEM to provide a remanufacturing service for an agreed set of models and products. Normally the cores are delivered in batches by the OEM to the remanufacturer. So the contract remanufacturers have a minimal uncertainty in terms of core supply compared to independent remanufacturers(Ridley, 2012). When sourcing spare parts, new parts suppliers usually need to be approved by the OEM to ensure quality. Please refer to Figure 23 in the case study section to view a diagrammatic representation of how a contract remanufacturer operates in the automotive sector.

1.2.8.3 OEM remanufacturers

OEM remanufacturers are in a better position as they have ready access to original product specifications. Often they have the capital to invest in technology and they possess the intellectual property rights for their designs. Their primary motive is market share rather than profit, unlike in independent or contract remanufacturers (Ridley, 2012). Though independent remanufacturers are sheer cost competitors, OEM remanufacturers have an advantage over them with quality and brand image.

Table 1 indicates a brief comparison of three types of remanufacturers. The table compares the factors in the context of automotive remanufacturing.

Table 1: Comparison of types of remanufacturers in automotive remanufacturing (Ridley, 2012)

Type of Remanufacturer	Primary Motive	Caters for	Key barriers	Strengths and opportunities
Independent	Profit	- Individuals - Vehicle dealerships	- Uncertain core supply - Poor access to technical knowledge - Difficulty in affording new technology - Competition from OEMs	- Flexible - Price competitive - Ability to cater for a wide range of products
Contract	Profit	- OEMs	- OEM controls the core supply - Selling price is fixed regardless of core quality - New parts have to be purchased from OEM approved suppliers	- Certainty in core supply - Specialisation - Cost competitive - Certainty in production planning
OEM	Market share	- Fleet/large-volume customers - Small-volume customers - Single-unit customers	- Cost competition from independent remanufacturers - **Cannibalisation*** of new product sales	- Access to full technical information - Greater certainty in core return - specialisation

* **Cannibalisation**

Cannibalisation could be in two forms in remanufacturing. One is market cannibalisation and the other is product cannibalisation. Market cannibalisation is a fall in demand for new products, due to the availability of cheaper remanufactured alternatives with same warranty and functionality. In the viewpoint of OEMs this could be a problem which may affect the revenue of the company.

The qualities of returned cores may vary more in some parts than others. This allows the remanufacturer the option of using good-quality parts of one core to be utilised in remanufacturing another core of the same category. So there might not be the same number of products remanufactured as cores received. This concept is referred to as 'product cannibalisation'. In some cases, product cannibalisation is due to the scarcity of replacement parts in the market (Guide Jr, 2000).

1.3 Research aims and objectives

The research aims to identify the significance and challenges of cleaning operation in automotive remanufacturing and thereby provide insights to reduce overall cost/effort of remanufacturing.

The following objectives are set in achieving the aim;

- **Objective 1:**To define the significance of the cleaning operation of automotive remanufacturing
- **Objective 2:** To find out the effort required for cleaning operation compared to other processes in remanufacturing
- **Objective 3:** To identify factors which cause the cleaning process to be more difficult and costly
- **Objective 4:** To reveal what knowledge could be applied to address the causes identified

1.4 Thesis structure

The first chapter sets the background to the research. It starts contextualising from sustainable manufacturing to closed-loop supply chains and then to remanufacturing and finally to cleaning. Then it introduces key end-of-use strategies and introduces remanufacturing process steps. It then discusses the research aim and objectives followed by research questions which were used to guide the research.

The literature review is presented in chapter 2. It starts with presenting the scope of the review and then presents the significance of remanufacturing. Then it discusses barriers to remanufacturing and identifies cleaning as a barrier. The next section reviews the few evidences on cleaning process remanufacturing followed by a two related topics of design for remanufacture and environmental impacts. Chapter concludes with discussing overall body of knowledge and identifies gaps in knowledge. Further it forms keys research questions.

The third chapter of the thesis discusses the research design. It starts with presenting relevant literature on research methodology in general. Then it present how the methods were selected based on research questions. Finally it elaborates how the case studies were performed and how data was analysed.

Chapter 4 presents the background and observation data of case studies with a summary to compare the companies investigated. Chapter 5 presents how the data analysis was carried out for literature, observations and interviews. The results and discussion chapter (Chapter 6) discusses how the research questions were addressed with major findings of the research. The last chapter, Chapter 7: Conclusions, concludes the findings and contribution to knowledge with giving future research directions.

2 LITERATURE REVIEW

This chapter explores current published literature on the use of remanufacturing as a reuse strategy. The objective is to understand the current body of knowledge and to identify gaps in knowledge. The chapter presents key strands of remanufacturing research and concludes by presenting gaps in knowledge leading to the research questions.

2.1 Scope of literature review

Published literature such as journal papers, conference papers and unpublished documentation like theses, presentations and discussion forums were used as sources of data for the review. Approximately 80 articles since 1981 – 2013 were reviewed. After the initial broad reading the scope was narrowed down to the cleaning process of remanufacturing. Firstly, it reviews the significance of remanufacturing in general and then barriers to remanufacturing. Then three key areas required to achieve the aim of research is discussed namely, cleaning, design for remanufacture and environmental impacts. Finally the review is expected to present the overall body of knowledge with different research strands in field and identifies gaps in knowledge. Discussion of other research strands which have no direct relevance to the aim and objectives of the research is excluded from the scope of the review.

2.2 How the literature review was conducted and analysed

Initially literature was referred to understand the process of remanufacturing in general. The scope was then narrowed as the gaps emerged in the areas of cleaning and environmental aspects of remanufacturing. Many databases were referred to, including Science direct, Springer, EThoS, eScholarship and Strathclyde library resources with search strings like 'Remanufacturing+Cleaning', 'Cleaning + Automotive remanufacturing', and 'Transmission remanufacturing'.

A content analysis was performed by thematically coding the relevant data in NVivo 10 - qualitative data analysis software. Over 20 themes were formed including, cleaning, design for remanufacture, methodology, legislation, environmental impact and many more as illustrated in 'Figure 47: Thematic coding using NVivo 10' in the data analysis chapter (Section 5). Then the coded content was analysed to identify the knowledge gaps and research questions forming the focus of the work described in Sections 3-7 of this thesis.

2.3 Significance of remanufacturing

It is vital to investigate the significance of remanufacturing as a sustainable manufacturing practice. There have been many studies undertaken throughout Europe and the USA comparing and contrasting available reuse strategies with various product types and industries. Sundin et al., (2009) mentioned that remanufacturing consumes about 50% to 80% less energy to produce compared with new product manufacture but with the comparable quality level about 85% by weight of components comprising of remanufactured products. Further there could be production cost savings from 20% to 80% compared with conventional manufacturing making remanufacturing a financially sound operation (Giutini and Gaudette, 2003; Sundin et al., 2009). A study by Ijomah and Chiodo, (2010) states that remanufacturing is often profitable compared to conventional manufacturing or recycling despite being a relatively novel concept.

Product remanufacturing is widely accepted as a sustainable end-of-use product reuse strategy (Zwolinski and Brissaud, 2008) in most industries, due to its unique advantage of retaining a greater portion of added value during the initial manufacturing stage (Giutini and Gaudette, 2003; Sundin and Lee, 2012) and has developed into a faster growing business than some of traditional industries (Guide Jr, 2000). A study on the significance of environmental savings through remanufacturing of compressors has shown that the amount of greenhouse gas emission of a remanufactured product is around 90% less than with the new compressor manufacture by OEM. It is also with a 50% cheaper price (Biswas and Rosano, 2011). When it comes to the automobile sector, it is estimated that 8-9 million vehicles are discarded every year in the European Union, of which a major proportion is recycled, making an average value of 75% by weight of a vehicle being recycled (Kumar and Putnam, 2008).

2.4 Barriers to remanufacturing

Even though the exact expression was not used, remanufacturing was a common life-extension technique for centuries for high-value low-volume products (Guide Jr and Van Wassenhove, 2009). Maintenance and rebuilding are common practices of life extension which are widely used by flight operators and public transport operators for their vehicle fleets, including locomotives and buses (Ferrer and Whybark, 2000). However, as a common business model for a wider product range beyond mechanical or largely metal-based equipment, remanufacturing faces a number of challenges. Table 2 below illustrates such barriers with industries of concern. The barriers depend on the type of remanufacturer.

Table 2: Barriers to remanufacturing

	Barrier	Affected parties	Reference
1	Part Proliferation – Introducing minor changes to products/parts. This makes it difficult to remanufacture as there are many parameters to concern (e.g. Different types of alternators for the same model of car for a given number of years of manufacturing)	Independent remanufacturers	(Hammond et al., 1998)
2	Products are not designed for active disassembly (DfAD) or designed for remanufacture (DfRem) which makes the remanufacturing process non-economical	All	(Chiodo and Ijomah, 2012) (Ijomah and Chiodo, 2010)
3	Reverse logistics – Due to cost of transportation, cost of storage, variability of return flow and handling issues.	All	(King and Burgess, 2005) (Guide Jr, 2000)
4	Variability of quality of cores - This makes the resource requirement for the remanufacturing processes to vary largely in terms of parts replacement, efforts on disassembly, cleaning, inspection and rebuilding.	All	(King and Burgess, 2005) (Guide Jr, 2000) (Ijomah et al., 2005) (Du et al., 2012)
5	Uncertainty of quantities and timing of returns - Production planning and control activities are complex for remanufacturers due to the stochastic nature of core returns	OEMs and Independent Remanufacturers	(Ijomah et al., 2005) (Du et al., 2012)
6	Difficulty of disassembly – As no standard technologies/methods to be followed companies use custom made tools and techniques for the disassembly process.	All	(King and Burgess, 2005) (Guide Jr, 2000) (Nasr et al., 1998) (Du et al., 2012) (Sundin et al., 2012)

7	Difficulty of cleaning	All	(Hammond et al., 1998) (Guide Jr, 2000)
8	Uncertainty in customer demand	All	(King and Burgess, 2005) (Guide Jr, 2000)
9	IPR restrictions – This is where OEMs will not provide technical specifications to Independent remanufacturers	Independent remanufacturers	(Ijomah et al., 2005)
10	Difficulty in pricing strategy – as the main cost component of part replacement can only be decided once the product reaches the inspection stage, passing both disassembly and cleaning operations.	All	(Ijomah et al., 2005)
11	Availability of cores	All	(Guide Jr, 2000)
12	Rapid technology advancements – with the advancement of manufacturing technology manufactures are releasing new product models with new features in much higher frequency than earlier in order to be competitive in the market	All, but mainly independent remanufacturers	(Guide Jr, 2000) (Ijomah et al., 2007)
13	Fashions, styles or market trends	All	(Ijomah et al., 2007)

Figure 8 represents a bird's eye view of the barriers to remanufacturing and how each sub factor affects the main factors. It is important to note here that the process of cleaning is identified as a barrier to remanufacturing as indicated in 7th row by (Guide Jr, 2000; Hammond et al., 1998) which is one of 13 barriers identified.

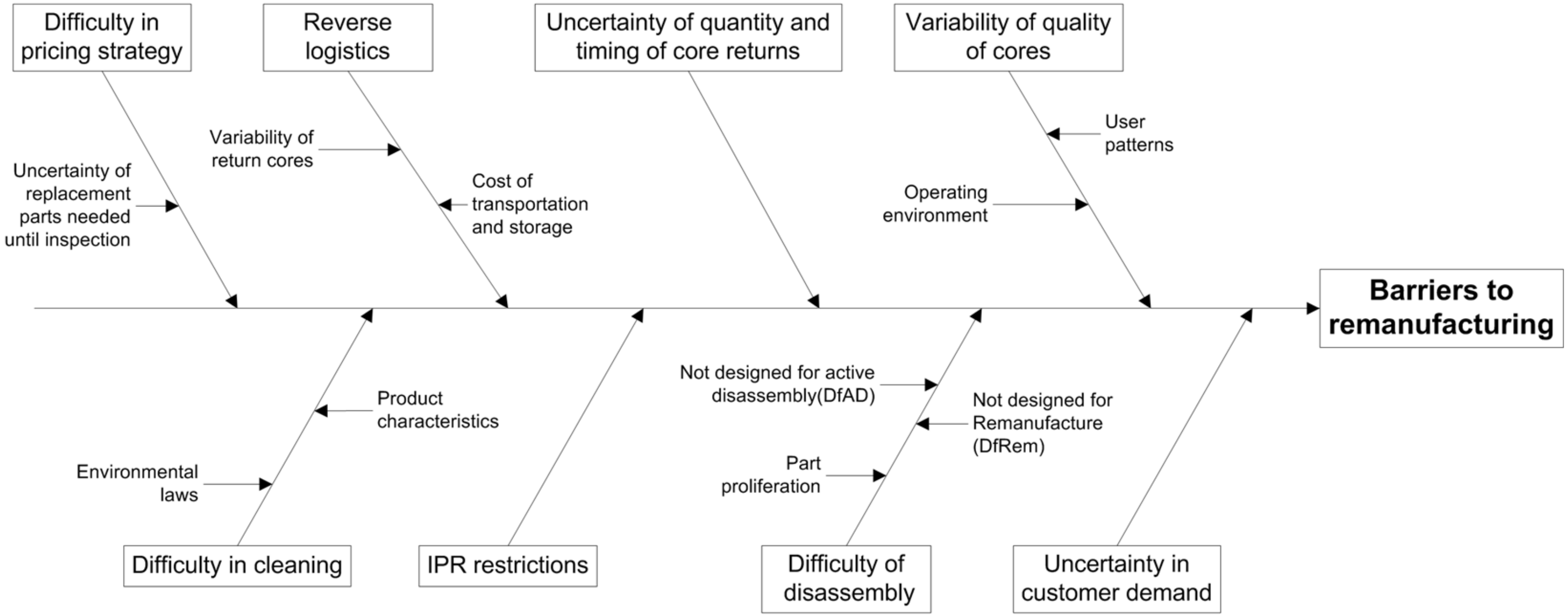


Figure 8: Barriers to remanufacturing

2.5 Cleaning

Cleaning has been identified as a barrier to remanufacturing in the previous section Figure 8. Among the key steps of remanufacturing (Figure 6), cleaning plays a major role in the quality of a remanufactured product. However, cleaning requires a considerable amount of resources, making it a major cost contributor in the complete remanufacturing process. It was found that the cost of cleaning is second only to new parts replacement (Figure 9) within reassembly operation in a survey undertaken in US automotive remanufacturing sector (Hammond et al., 1998).

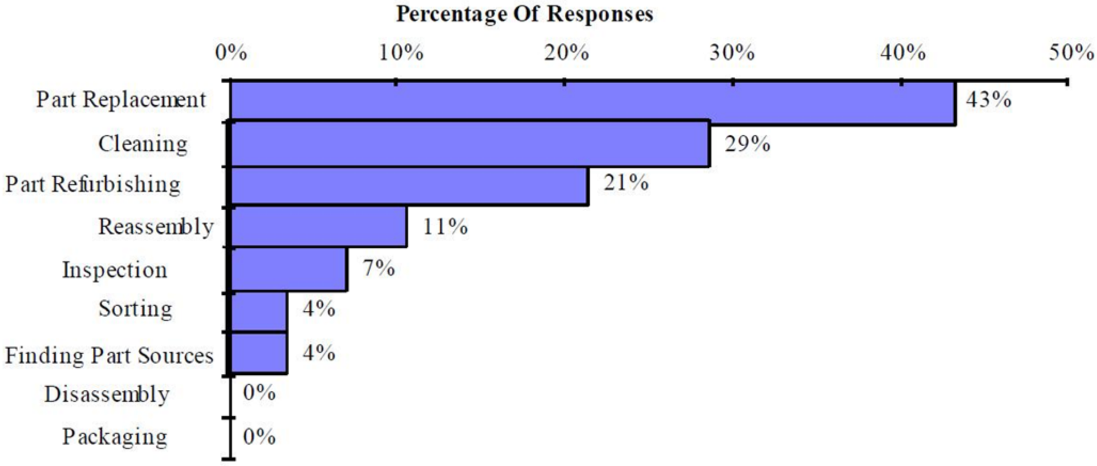


Figure 9: Most costly operations in remanufacturing (Hammond et al., 1998)

A study on Swedish remanufacturing, involving automotive and household appliances such as the washing machine remanufacturing industry by Sundin and Bras, (2005), has indicated cleaning and repairing steps as the most critical in the remanufacturing process.

The cost of cleaning is largely due to it being labour intensive, as there are few automated or machine-driven processes for cleaning. Other costs arise from consumables like chemical detergents and factory overheads, such as electricity to operate cleaning machinery. So the time spent on cleaning is vital in controlling the cleaning costs involved. In an assessment on US remanufacturing practices Nasr et al., (1998) indicate that cleaning accounts for a major portion of total remanufacturing processing time with an average of 20% spent on the cleaning operation. One more reason for these excessive cleaning times is the requirement of multiple processing within the cleaning operation (Guide Jr, 2000). A study on energy intensities in diesel engine component manufacture in US by Sutherland et al., (2008) states cleaning remains a dominant energy consumer for remanufacturing of all of the engine components.

2.5.1 Cleaning methods used in remanufacturing

There is a paucity of published research evidence of cleaning during remanufacture. It is hard to find details of any methods used in cleaning and optimisation of the cleaning effort to reduce the cost of remanufacturing. Among the few entries in remanufacturing, Na and Park, (2012) discusses various cleaning methods available for diesel particulate filter (DPF) remanufacturing such as high temperature air washing and ultrasonic wave cleaning.

A life cycle study by Biswas and Rosano, (2011) on remanufacturing of compressors used in the refrigeration and air-conditioning industry used extensive cleaning operations involving chemicals such as phosphoric acid, alkaline and decarbonisers, mixed with hot water for cleaning and washing purposes. However, there is lack of publications on automobile gearbox and engine-cleaning processes during remanufacture.

2.5.2 Factors making cleaning more difficult and costly

Though the literature on cleaning operations specific to remanufacturing is lacking, several factors can be identified from the very few studies that have been undertaken. A study on issues of US automotive parts remanufacturing by Hammond et al., (1998) discusses a wide range of reasons for higher cleaning costs. The main reason is identified as the Environmental Protection Agency (EPA) issues followed by a variety of reasons such as excessive debris, part/orifice sizes, material used and corrosion. Please refer to Figure 10 for the extract of their study. However, the cost of complying with environmental regulations is of less influence to small-scale remanufacturers as their emissions to the environment from cleaning residue is much less than that of large-scale organisations. This keeps their cost of effluent treatment processes to a minimum. This indicates the dependence of the size of the organisation with its associated cleaning costs.

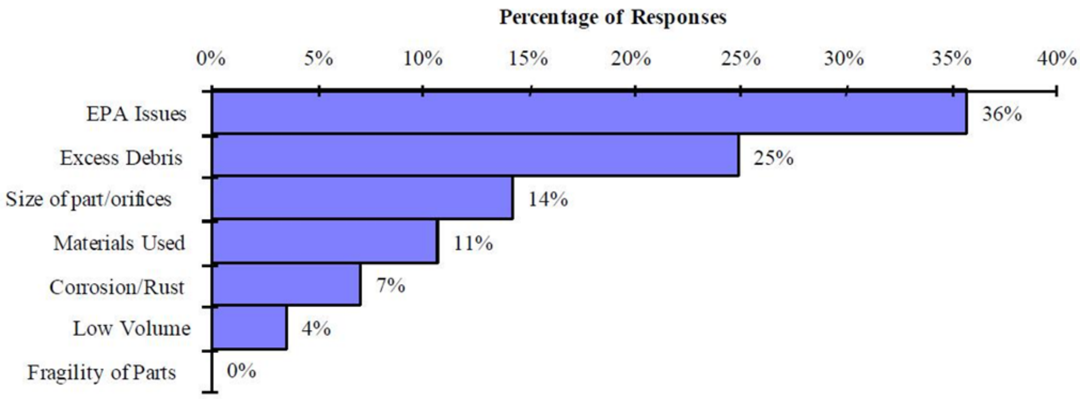


Figure 10: Factors which make cleaning more difficult (Hammond et al., 1998)

Hammond et al., (1998) further argue that use of lighter-duty materials, such as plastic or aluminium in place of steel or cast iron, increases the fragility and hence weakening of components, which increases the tendency of breakage during disassembly and cleaning. However this is highly dependent on the product under consideration and can be considered under the already identified factor of ‘Material used’. Furthermore, in the automotive industry, the majority of fragile components are replaced as it is not economical to clean and reuse. Remanufacturers hardly want to risk the quality/warranty of the remanufactured product by reusing these lightweight and low-value components. Sundin and Bras, (2005) draws the attention of product designers to focus on ease of separation, wear resistance, ease of access and ease of handling to facilitate cleaning and repair, which are identified as the most critical steps of remanufacturing. A comprehensive survey undertaken by Guide Jr, (2000) in the US remanufacturing industry covering a wide range of remanufacturers has revealed that part material and part sizes cause additional difficulties in cleaning operations during remanufacturing. Table 3 summarises the factors found in literature that make cleaning more difficult.

Table 3: Factors making cleaning more difficult

	Factors making cleaning more difficult
1	Environmental regulations
2	Excessive debris
3	Part/orifice sizes
4	Type of materials used
5	Level of corrosion

2.6 Design for remanufacture (DfRem) and cleaning

Previous section has identified part sizes/shapes and material types cause cleaning more difficult and costly. This section tries to identify any design level factors can contribute towards overcoming such issues. This could be product design or process design.

Conventionally, products are designed for efficient manufacturing. Manufacturing processes have also facilitated fast and efficient assembly and finishing processes mostly involving automated production lines. The design stage of products and processes is mainly concerned with quick and efficient modes of production methods, easy to handle material, quick and easy methods of fastenings and assembly methods, etc. However, this single-sided view does not help efficient product-recovery activities. It has found that poor understanding or poor knowledge on design for remanufacture is a main barrier in remanufacturing (Chiodo and Ijomah, 2012; Ijomah and Chiodo, 2010) as discussed in *2.4 Barriers to remanufacturing*. For example, a product designed for fast assembly does not necessarily mean that it can be disassembled at the same phase during recovery activities. The requirement of making the product recovery process efficient has made the designers consider the product recovery parameters triggering the terms design for remanufacturing, design for disassembly etc. In a state-of-the art review of published work by Ilgin and Gupta, (2010) brought three major related concepts under design for X (DFX) namely design for environment (DFE), design for disassembly (DFD) and design for recycle. All these show the importance of design for recovery activities but there was no indication on design for cleaning (DfC).

Ijomah et al., (2007) in their study on developing design for remanufacturing guidelines conducted with UK remanufacturers have indicated four key concerns in designing products for remanufacture. The first is the use of non-durable or non-robust material which may cause failures during the remanufacturing process or by the time the core is received it may be beyond refurbishment. But there was no focused discussion on this failure is taking place during which process of remanufacturing: disassembly or cleaning. Hammond et al., (1998) presented a similar argument in their study in the US automotive remanufacturing industry, where the use of lighter-duty material, such as plastic or aluminium in place of metal, may cause breakages during remanufacture.

The second main concern according to Ijomah et al., (2007) is the joining technologies used during manufacture, such as snap fits, some types of welded joints, riveted joints and adhesive bonds. These joining types may make the manufacturing process efficient but cause destruction and/or excessive delays during disassembly in the remanufacturing process. It appears that the main focus here is on ease of disassembly rather any other steps of remanufacturing. Some joining methods, like welding or adhesive bonding, may require excessive cleaning if they are to join again for remanufacture, which was not discussed in this paper. The third consideration is the features of some products which require banned substances or processes. Finally, the concern for design for remanufacture, according to Ijomah et al., (2007), is that the features of some products render them not cost effective with available remanufacturing technologies. None of the DfRem concerns presented here in Ijomah et al., (2007) discusses the effects on cleaning operation. Further, Ijomah, (2010) also argues design for remanufacture requires products to be designed for ease of disassembly which is again silent on ease of cleaning.

There have been several studies on designing for remanufacture efforts in different industries. One such example is the industry of cellular phone remanufacture where one of the main costs involved is the purchasing of cosmetic parts, like phone housing, from OEMs due to the vast range of phone varieties. Seliger et al., (2003) discussed a design of modular housing platform for multiple cellular phone models to reduce the costs of remanufacturing. A research on design for automatic end-of-life by Sundin et al., (2012) in the industry of toner cartridges and liquid crystal displays has shown that there are three general product trends and they are in conflict with automatic disassembly. Namely, the tendency of products becoming more heterogeneous or complex, tendency of products becoming sleeker and tendency of using more proprietary joints for assembly. These trends are silent on the cleaning process and whether those trends are applicable to automotive remanufacturing industry is also to be investigated.

Hammond et al., (1998) mentioned that many products in the automotive remanufacturing industry, especially complex products like engines, are not designed to be serviced beyond the routing/planned maintenance schedule, which leaves no option of product recovery other than recycling. However, it is interesting and encouraging that some studies in photocopier industry have indicated that products designed for remanufacture are generating more savings during remanufacturing than the products which are not designed for remanufacture (Kerr and Ryan, 2001). Sundin and Bras, (2005) have mentioned that the cleaning and repairing steps are the most critical activities, in remanufacturing of household appliances and automotive parts, drawing the attention of designers to design products with ease of access, ease of handling, ease of separation and wear resistance. This has a direct link to cleaning in automotive industry with design for remanufacture despite a detailed discussion on cleaning is not evident.

So far, the discussion has been on design of the product itself to facilitate remanufacture, but it is worthwhile to investigate whether the entire business model can be designed to facilitate remanufacture. One such practice could be the product service system (PSS) and/or functional sales. These models are being practised in a variety of industry sectors such as aircraft turbines, automobiles, photocopiers, car sharing and IT solutions (Boehm and Thomas, 2013). In support of this business model, the products used in PSS could be designed facilitating ease of maintenance, repair and remanufacture while leaving the company with a cost advantage (Sundin et al., 2009).

2.6.1 Product service systems (PSS)

Product service systems can be seen as a business model which facilitates process level design which facilitates remanufacture. A review article in state-of-the-art of product service systems defines PSS as “an integrated product and service offering that delivers value in use” (Baines et al., 2007). Traditionally the manufacturer/supplier was transferring the ownership of the product to the customer. It was up to the customer to use the product during its economic life and discard it. The supplier was offering only after sales service for a limited period of time for free or discounted rates. However, the trend of PSS came in to practice where the manufacturer/supplier sells the service integrated with the product as opposed to the product only. The product may physically be at the customer’s premises but the ownership is with the supplier. The customer pays the price for a unit service rendered and the supplier takes care of all routine maintenance and upgrades. This model is famous with photo copier, rent-a-car operators etc. The concept is referred to as a ‘Product service systems (PSS)’. Recent review on three main disciplines, Business Management, Engineering and Design and Information Systems has defined a Product-Service System (PSS) as “ an integrated bundle of products and services which aims at creating customer utility and generating value” (Boehm and Thomas, 2013).

Product life cycle thinking is key when designing product service systems (Sundin et al., 2009). EPR is encouraged with PSSs as the ownership is with the manufacturer/supplier, the end-of-life decision has to be made by suppliers which encourages remanufacturing as well. Remanufacturing is preferred over material recycling as it preserves the associated economic and environmental values (Hammond et al., 1998). However, Sundin et al., (2009) argue that the motive for PSS is hardly due to environment savings, but mostly due to customer demand and profit motive.

2.7 Environmental impact of remanufacturing

The objective of this section is to find out evidence of environmental impacts of remanufacturing specifically during cleaning operation and identify gaps in knowledge. Manufacturers are encouraged to undertake environmentally-conscious practices for the design, development, manufacturing, distribution, service and end-of-life treatment of their products by the growing awareness of consumers, businesses, governments and society-at-large (Du et al., 2012; Subramoniam et al., 2010). This practice of extended producer responsibility (EPR), which is defined as "an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle" (OECD, 2004), draws their focus from short-term profit targets to more long-term environmentally less harmful production. EPR encourages closed loop supply chains, where post-consumer stage products are brought back to reusable condition through various means, including remanufacturing. The main goals of EPR include product reuse, waste prevention and reduction, promoting the use of recycled material, hence reducing the natural resource extraction, incorporating the environmental cost in product prices and improving energy recovery rates (Nnorom and Osibanjo, 2008).

Unlike in manufacturing, the environmental performance of remanufacturing has not been well quantified (Sutherland et al., 2008). Such environmental analysis attempts using life-cycle assessment techniques are lacking for products with multiple-use cycles (Krikke, 2010). Further, in the area of remanufacturing there has been a lack of environmental assessment studies and an easy way of quantifying environmental impact would be beneficial for industries in strategic decision making and complying with relevant legislation (Sundin and Lee, 2012). The current literature does not specifically focus on the impact from cleaning operation alone rather focuses on the impact of entire remanufacturing process. However, the contribution to environmental impact due to liquid waste emitted by cleaning process may be high compared to other steps of remanufacturing which is yet to be quantified.

2.7.1 Design for environment (DfE)

Integrating environmental considerations at the product and process design stage is referred to as design for environment (DfE) (Sundin et al., 2009). An interesting and contradicting argument to the traditional view of using as little as possible material for initial manufacture is brought in by Okumura et al., (2003) in which they argue that using excessive material to improve the physical properties like strength and yield at the point of production will facilitate using the product for several functional lives. Under this scenario, it is essential to consider the cost to the environment over all those life cycles rather than only to the initial product life cycle. Using the product in several lives by repetitive remanufacturing has to undergo same number of cleaning and other operations using energy and chemicals as illustrated in Figure 11. Cleaning may sometimes appear in two times for same product, core cleaning before disassembly and component cleaning after disassembly. A quantification of the impact from energy used and disposed detergents, degreasers and other consumables have to be taken in to consideration during the process of DfE.

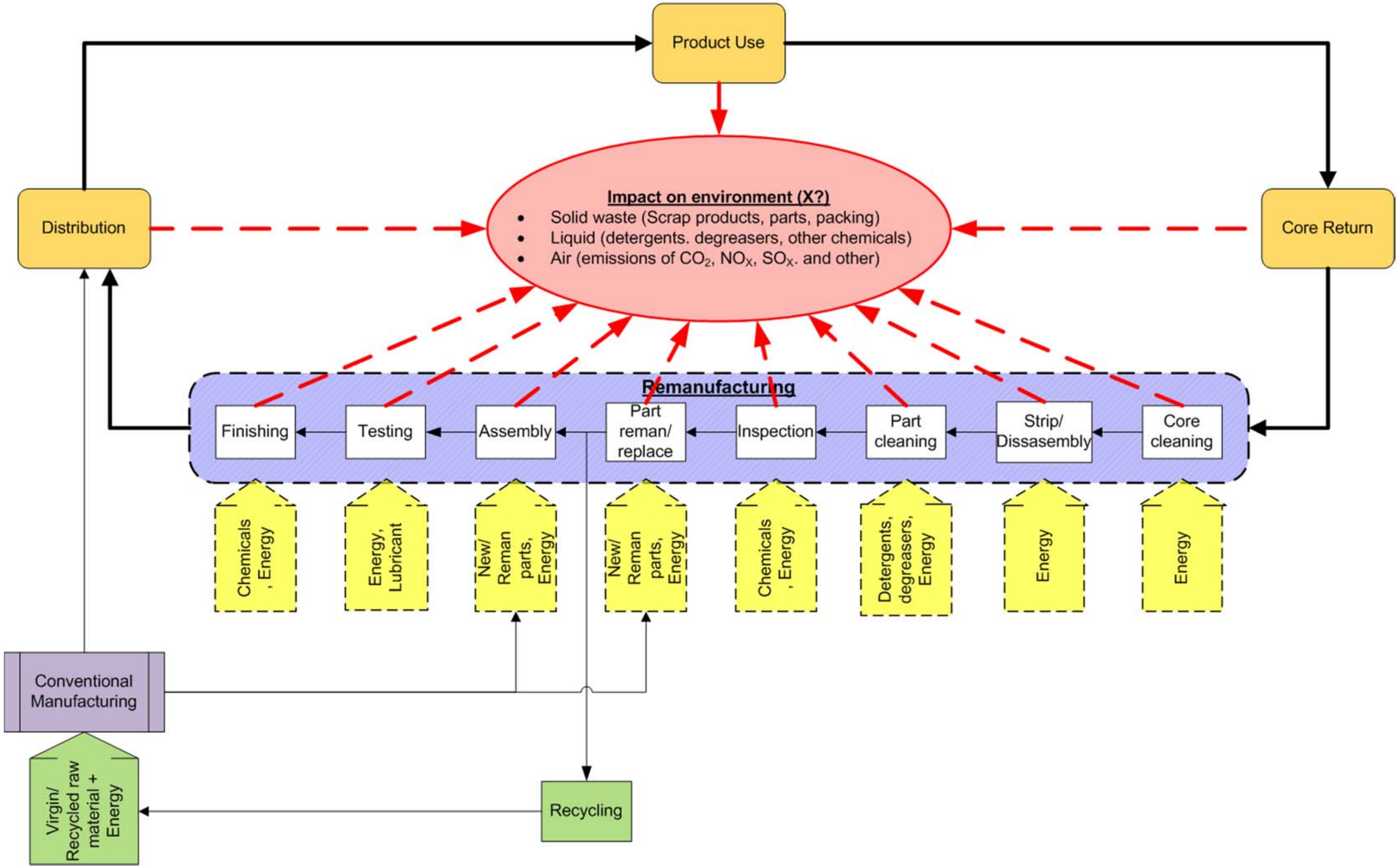


Figure 11: Environmental impact of product remanufacture

2.7.2 Legislation

It is common practice for manufacturers to make decisions solely on the profit motive. They may opt for cheaper raw materials, cheaper production processes and address market trends in a competitive way. This has caused extensive extraction of natural resources, increased emissions of Greenhouse and other toxic gases and complications with disposal of solid and liquid waste. This leads to an imbalance of the ecological system and with the increasing world population there seems no slowing down of these adverse effects, rather it is getting worse at an increased rate. Authorities have taken measures to incorporate responsibility for the environment to the manufacturers themselves and to make the general public aware of environmentally friendly ways of using products by way of legislative directives. They have incorporated a financial cost towards the harm to environment in motivating product users and manufacturers (Kumar and Putnam, 2008).

This section gives a brief introduction to such directives related to product manufacture, usage and disposal. The European Union has been the leader in introducing most of such directives including End-of-Life vehicles (ELV) directive, Waste Electrical and Electronic Equipment (WEEE) directive, Restriction of Hazardous Substances (RoHS) directive (Kumar and Putnam, 2008).

2.7.2.1 End-of-life-vehicles directive - 2000

This is the Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles which apply to vehicles and end-of-life vehicles including their components and material. The directive addresses major areas, including reducing waste production, organising waste collection and waste treatment, prioritising reuse and recovery of waste, facilitating, dismantling and evaluating progress of the above activities.

The aim of reducing the amount of waste generated from vehicles is being achieved by encouraging vehicle manufacturers and importers into the European Union to design and manufacture vehicles facilitating reuse and recycling, to limit the use of hazardous substances and to develop methods to integrate recycled material

("DIRECTIVE 2000/53/EC on end-of life vehicles," 2000, "End-of-life vehicles," 2013).

Prioritising the rate of reuse and recovery is being done by setting recovery targets in the member states. The directive set targets for rate of reuse and recovery to achieve a minimum of 85% by an average weight per vehicle by 2006. This target has increased to a minimum of 95% by year 2015. The figures for target rate of reuse and recycling is 80% and 85% by an average weight per vehicle and year for years 2006 and 2015 respectively. Facilitating disassembly is assured by requesting producers meet the materials and components coding standards. The Commission will be responsible for setting relevant standards.

The directive specifies the evaluation of progress through implementation reports. This is achieved through requesting the economic operators (producers, distributors, dismantlers, etc.) to publish information on design of vehicles and its components, end-of-life treatment methods, improvements of methods of reuse, recycling and recovering end-of-life vehicles and the progress made in these fields. The member states shall provide this report to the Commission every three years and within nine months of receipt of it, the Commission shall publish a report on the implementation of the directive ("DIRECTIVE 2000/53/EC on end-of life vehicles," 2000, "End-of-life vehicles," 2013).

The core aim of the directive is to promote the reuse and recovery of end-of-life vehicles. However, a controversial argument is made by (Seitz, 2007) in her study on motives for product recovery with a case of engine remanufacturing practice of OEMs in Europe. The research concludes that environmental legislation, such as End-of-life vehicles directive, have only a low degree of influence on OEMs in automotive remanufacturing. She further argues that the classic reasoning of environmental pressure as a motive could not sufficiently explain the rationale behind automotive remanufacture in this particular case.

2.7.2.2 Waste Electrical and Electronic Equipment (WEEE) Directive – 2003

This is a European community directive on how to deal with waste electrical and electronic equipment, which became European law in February 2003. The WEEE directive sets targets of collection, recycling and recovery for all types of electrical goods with a minimum rate of 4 kilogrammes per head of population until 2015. Further, it targets an annual collection rate of 65% EEE placed on the market in the preceding three years from 2019 (“Directive 2012/19/EU on waste electrical and electronic equipment (WEEE),” 2012).

EPR has a vital role to play in controlling the electronic waste transfer to developing countries where proper recycling or product recovery facilities are hardly found (Nnorom and Osibanjo, 2008). When it comes to reverse logistics channels, OEMs prefer to outsource the product recovery activities to third parties rather than setting up their own reverse logistics channels when complying with WEEE directive (El korchi and Millet, 2011).

EPR encourages the eco-design of electrical equipment and reducing the impact on the environment by improving energy efficiency during manufacture, use and recovery stages. However a case study on eight European companies in the lighting sector by Gottberg et al., (2006) has shown that imposing financial burdens alone on manufacturers for collection and recycling of WEEE is not a sufficient enough motivator for eco-design.

2.7.2.3 Restriction of Hazardous Substances (RoHS) in electrical and electronic equipment Directive – 2006

This is a sister EU directive to WEEE. The directive defines Electrical and Electronic equipment’ or ‘EEE’ as “equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation, transfer and measurement of such currents and fields and designed for use with a voltage rating not exceeding 1000 volts for alternating current and 1500 volts for direct current” The directive specifies and limits the member states from using a number of substances used in EEE. These include Lead, Mercury, Cadmium, Hexavalent chromium, Polybrominated biphenyls (PBB), Polybrominated diphenyl ethers (PBDE) (“DIRECTIVE 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment,” 2011).

However, King et al., (2006) pointed out an anomaly within the RoHS directive, where it provides concessions that allow the use of concerned substances during the repair of an existing product whilst not allowing the use of the same during remanufacturing, claiming that they are being sold again.

2.8 Conclusions from the literature

This section gives an overview to the overall state of knowledge found from literature on remanufacturing with diverse research strands. It further leads to identify gaps in knowledge and develop research questions to direct the research.

2.8.1 Overall state of knowledge

There are seven different research strands identified form literature as illustrated in Figure 12.

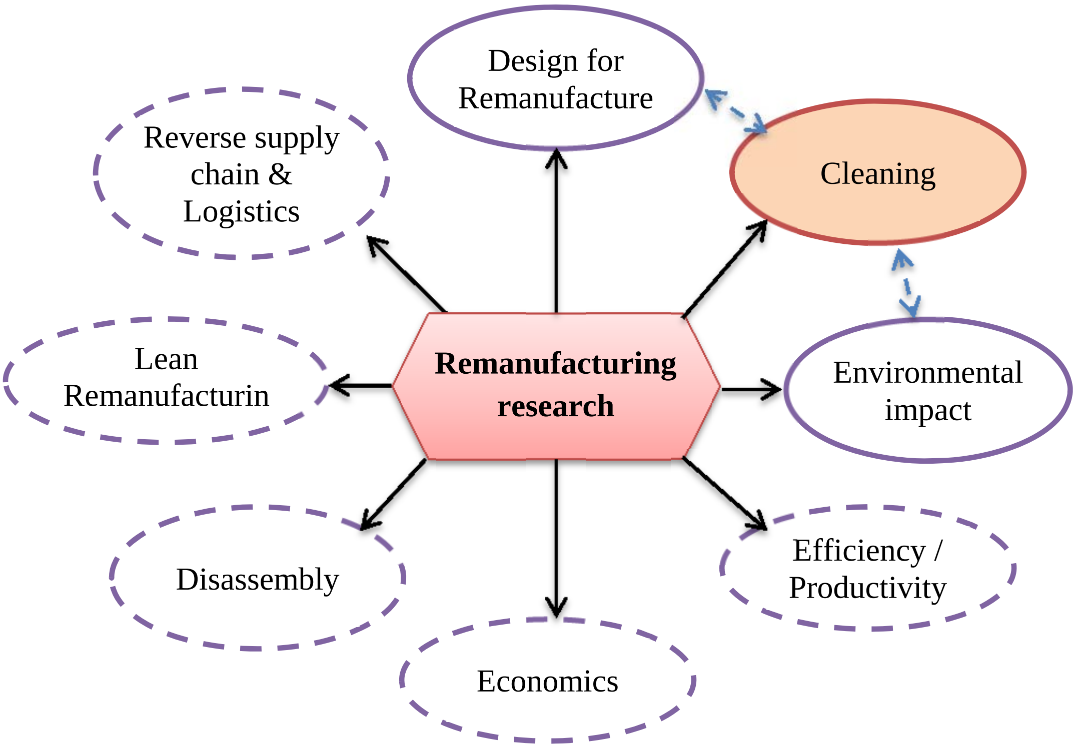


Figure 12: Different research strands in the filed

Out of that three strands were discussed in the literature review section considering the scope of research. These are design for remanufacture, environmental impact and cleaning. Other strands, which are denoted with dotted lines in Figure 12, were excluded from the discussion as they are out of the scope or they have a weak relationship with the gaps found.

- **Cleaning –** Cleaning was identified as a barrier for remanufacturing in Table 2. Only four articles have mentioned cleaning as an issue and only one article has investigated factors for high cleaning costs.
- **Design for remanufacture (DfRem**) - This is the discussion about how to facilitate remanufacturing at the product design phase which was discussed in section *2.4.* There were 13 (26%) sources/articles coded on DfRem out of 50 sources coded during the literature analysis process using NVivo. Most of the references cited the benefits of DfRem to ease of disassembly process but hardly any were discussing the ease of cleaning.
- **Environmental impact –** The broader relation of the environmental impact and remanufacturing was discussed. There were 16 (32%) references mentioning on environmental impact and savings through remamufacturing. However, impact for individual process steps, especially with cleaning energy and consumables, was not evident from literature.

DfRem and environmental impacts has several interrelations with cleaning process as denoted by two-way arrows in the Figure 12.

2.8.2 Gaps in knowledge

From the literature review two key under-researched areas were identified. The first is the environment impact assessment of products with repetitive-use cycles using remanufacturing. Environmental impact analysis for single-use cycle is common and popular as a marketing tool for products, while complying with environmental directives to reduce ecological footprint. However, such environmental analysis attempts at life-cycle assessment techniques are lacking for products with multiple-use cycles (Krikke, 2010). Further, in the area of remanufacturing there has been a lack of environmental assessment studies (Sundin and Lee, 2012) and unlike in manufacturing, the environmental performance of remanufacturing has not been well quantified (Sutherland et al., 2008). Hence a quick and easy method of quantifying these environmental impacts will be beneficial for industries in strategic decision making and complying with relevant legislation. However, this gap in knowledge is not chosen to address in this research considering the inputs from case studies and access to data.

The second gap area identified is the higher cost/effort of the cleaning operation during remanufacture. This extends the total cost/effort of the remanufactured product, making it less attractive in the market. There was only one research publication targeting the cleaning operation of the remanufacturing process in automotive industry. No research data was found on optimisation of cleaning methods in terms of machine or labour hours. Hammond et al., (1998) have identified cleaning as the second most costly operation during automotive remanufacturing. It is required to answer why cleaning is essential in remanufacturing which forms the 1st research question for this research. They (Hammond et al., 1998) have further found several important factors which directly influence higher cleaning costs. However, evidence on any research attempts on improving/optimising the cleaning operation or in depth analysis on those factors can hardly be found in existing literature. This has formed the second research question: How much effort is required for cleaning and third research question: Which factors make cleaning more difficult. These research questions will direct this research in narrowing gap in knowledge.

Having discussed the literature summary it is concluded that cleaning during remanufacture is a key under researched area which has a big potential to research. It is required to study the UK remanufacturing industry to confirm the claims made in literature and to identify new areas of concern. Finally, it is expected to find what knowledge could be used to improve the cleaning operation and make more economical for remanufacturing.

3 RESEARCH DESIGN

This chapter presents a background on research philosophy, methodology and selections of case study method based on research questions.

3.1 Methodology literature

The context of research methodology in management research is illustrated in Table 4. The table defines the key philosophies of management research from ontology to research methods.

Table 4 : Ontology, Epistemology, Methodology and Methods (Easterby-Smith et al., 2008)

Ontology	Philosophical assumptions about the nature of reality
Epistemology	General set of assumptions about the best ways of inquiring into the nature of the world.
Methodology	Combination of techniques used to enquire into a specific situation.
Methods	Individual techniques for data collection, analysis, etc.

The methods or techniques available under the methodology chosen may heavily depend on the choice of one's research questions.

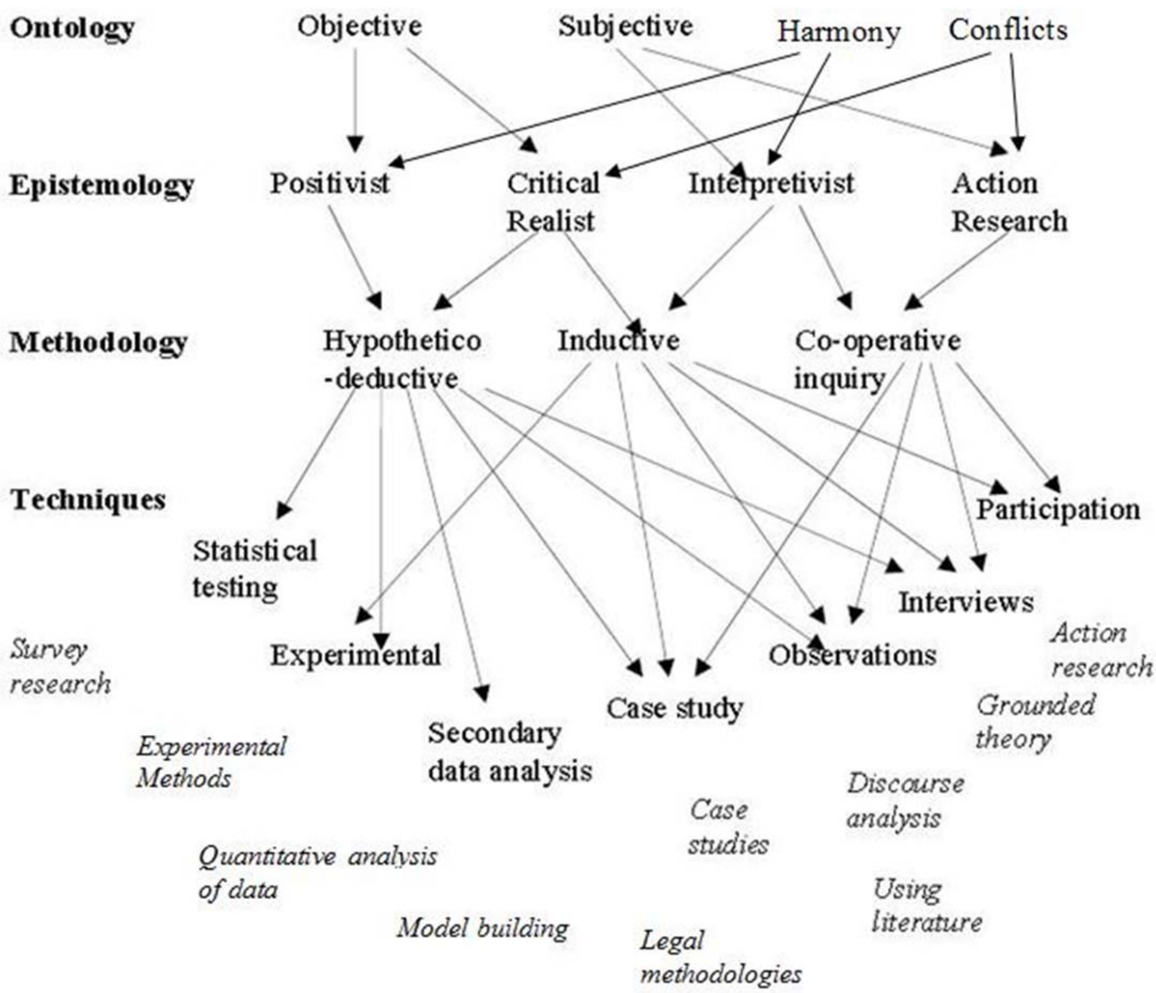


Figure 13: Research design map (Quigley, 2012)

A clear illustration of derivation of research methods, starting from ontology followed by epistemology, is presented in Figure 13. The first level shows the two major ontologies debating whether there is an objective truth (Objective ontology) or truth is subjective based on the observer (Subjective ontology). The next level elaborates the four epistemologies which are the ways in which how to look into the reality. Positivism and Critical realism believes there is an objective truth whereas the Interpretivism believes that reality is subjective. Level 3 of Figure 13 presents the three methodological arguments, deductive - where you make a hypothesis and look into prove it or disprove it, inductive – investigating for a reality without any hypotheses and letting it to emerge from the research, and the last co-operative enquiry. The final level presents the available methods or techniques that can be used based on a preferred philosophical assumption. This diagram is used identify which methodologies to adopt considering the research questions in the ‘3.2 Methods selection’ section.

3.1.1 Case study method

Meredith, (1998) explains case study as a method which ‘typically uses multiple methods and tools for data collection from a number of entities by direct observers in a single, natural setting that considers temporal and contextual aspects of the contemporary phenomenon under study, but without experimental controls or manipulations’. Further, ‘The methods and tools employed include both quantitative and qualitative approaches as well as obtrusive and unobtrusive methods. Example entities include financial data, interviews, memoranda, business plans, organization charts, tools and other physical artefacts, questionnaires, and observations of managerial or employee actions and interactions’(Meredith, 1998).

Case study research can involve either single or multiple cases and numerous levels of analysis, to embrace quantitative and qualitative data, and to embrace multiple research paradigms’ (Dooley, 2002; Yin, 1981). Case study answers the ‘Why’ and ‘How’(Yin, 1981) questions in the research and is a strategy which focuses on understanding the dynamics present within single settings (Eisenhardt, 1989). Table 5 shows the pros and cons of case approach.

Table 5: Advantages and disadvantages of case research methods – extracted from (Meredith, 1998)

	Case research
Advantages	Relevance
	Understanding
	Exploratory depth
Disadvantages	Access and time
	Triangulation requirements
	Lack of control
	Unfamiliarity of procedures

3.2 Methods selection

Selection of a methodology should be driven by the types of research questions formed. And also it is important to investigate the dominant philosophical and methodological approaches of the similar research fields. This section helps to figure out appropriate methods to conduct the research.

3.2.1 Research questions

The following research questions are formed to achieve the objectives of the research. The questions are set to address the identified research gap.

1. **Why cleaning is essential in products remanufacturing?** This will help investigate the technical and non-technical requirements of cleaning during remanufacturing and to ascertain the significance of cleaning among other processes.

2. **How much effort is required for cleaning compared to overall remanufacturing effort?** This is to enquire the amount of effort put towards cleaning

3. **Which factors make cleaning more difficult?** This question is expected to identify causes of higher cleaning efforts/cost which, in turn, will help to find solutions.

4. **What knowledge could be used to make cleaning easier and more economical?** The intention here is to acquire the expert knowledge of the personnel engaged with remanufacturing. This will introduce new knowledge for achieving the aim of the research, i.e. to reduce the efforts of remanufacturing.

Based on the characteristics of the research questions it is clear that the research is of descriptive nature as the first two questions asks ‘why’ and ‘how’ questions and the last one asks ‘what’ question which are trying to describe and explore the situation using multiple sources. Thus it leads in the direction of multiple case study methods as explained in (Yin, 2003). The literature review also revealed that there is a paucity of studies on automotive cleaning during remanufacturing with a greater depth.

Hence this research questions are set to explore the current situation of cleaning in automotive remanufacturing industry and identify potentials to overcome any related issues. This will require the use of case study method with multiple cases considering the all types of remanufacturers as the scope of cleaning for each remanufacturer may be different from one to another.

3.2.2 Methodological approaches in the field

In the Faculty of Engineering, most research work assumes a positivist paradigm with deductive methodology using methods like statistical testing or experiments. However, when it comes to Engineering Management, philosophical assumptions tend to lean towards critical realism or bounce between positivism and critical realism or bounce between critical realism and interpretivism as illustrated in Figure 14and Figure 15.

The methodologies used by previous researchers in the field were studied through the published work. Table 16 in the appendix I shows a representative sample of published papers (20 paper sample) analysing the methodologies. From Table 16, it can be seen that case study and mathematical modelling are the most commonly used techniques in previous research. Almost half of the studies (45%) have employed case studies for their research, whilst 35% have used mathematical modelling. Further 10% of researches have used the survey research method. Even though this is not a large enough sample to come to a statistical conclusion, it represents a fair enough picture of current published literature.

Past research work (Table 16 in the appendix I) demonstrates the use of both quantitative and qualitative modes of inquiry and also mixed methods of research. This is further justified with the research work presented in a few of the recent doctoral theses in the field (Ates, 2008; Hatcher, 2013; Ijomah, 2002). Qualitative and quantitative paradigms, which are the basis of research design, have their roots in the philosophical thinking of phenomenology and positivism (Easterby-Smith et al., 2008). They further argue that in the actual practice of research, even self-confessed extremists do not hold consistently to one position or the other (Easterby-Smith et al., 2008). A useful compromise which can combine the strengths and avoid the limitations of positivist and interpretivist paradigms is critical realist paradigm while it has its own strengths and weaknesses. Critical realist view recognises the value of using multiple sources of data and perspectives(Easterby-Smith et al., 2008). It can be concluded that the field is using multitude of philosophical and methodological approaches. However, the focus of remanufacturing research group is more inclined to critical realist and interpretivist paradigms with mostly qualitative modes of inquiry.

3.2.3 Selected method: Case study

Considering the nature of research questions and the background of the field it was decided to use multiple case study method with qualitative mode of enquiry. Even though 'How' question (RQ2: How much effort is required for cleaning?) is giving quantitative data (time and cost), the objective was to get an idea of significance of cleaning and not to perform a quantitative inquiry. As the research is mainly based with experiences and perception of stakeholders and understanding the contextual aspects of a natural setting (Meredith, 1998) and exploring objective reasons based on nature of research, a critical realist approach using case study method (Figure 14) was selected with a qualitative mode of inquiry(Creswell, 2002).

The research design map in Figure 14 encircles the methodological choices followed in this research. The nature of research requires the investigation of the existing remanufacturing facilities and their concerns in product remanufacturing process. This requires interviewing the decision makers in the industrial environment.

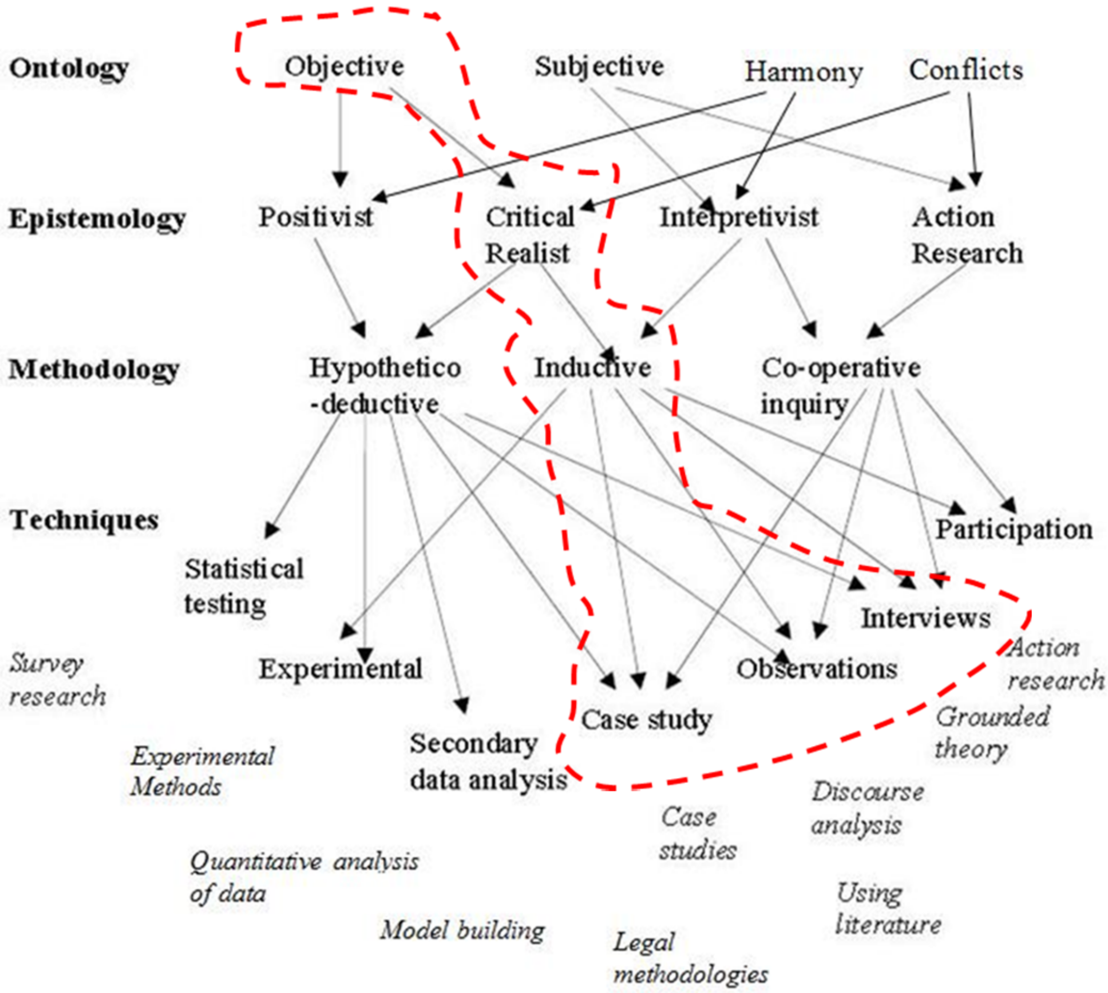


Figure 14: Selection of Methodology

Figure 15 illustrates well how the case study method positions itself in the wide philosophical paradigms. The four main epistemologies, Positivism, Critical realism, Interpretivism and Action research are positioned in the diagram considering the ontological extremes of objectivity and subjectivity. The case study method by Yin (Yin, 2003) is positioned between two ontological assumptions and leaned towards independent axis of the diagram. This supports the methodology selection for this research as explained using Figure 14 earlier.

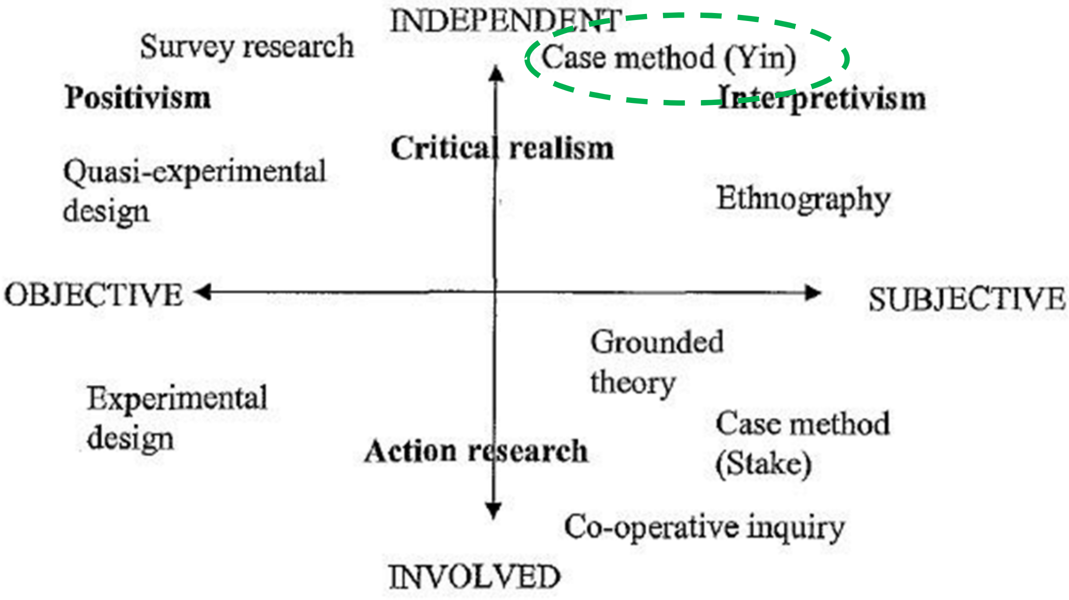


Figure 15: Research Design and method choices (Easterby-Smith et al., 2008)

3.3 Design of case studies

The scope of research is limited to study of cleaning process during automotive remanufacturing process. This section explains the criteria for selection of companies and how the data collection process was carried out.

3.3.1 Criteria for selection of companies

The criteria for selection of case studies were mainly based on the nature of products they remanufacture. All three companies were in the automotive industry and they all were remanufacturing transmissions and engines which improves the comparability among cases. Second criterion was to get a cross sectional view of the automotive remanufacturing sector which comprise of all three types of business models. These are independent, contract and OEM remanufacturers under which the three selected companies A, B, and C belong to, respectively. Final and most important factor was the accessibility to companies. The distance from Glasgow and getting permission to visit the facility, observe and interview personnel were key concerns when selecting companies.

3.3.2 How the case studies were conducted

Three automotive remanufacturers of transmissions, engines and related parts were studied. Companies A, B and C were representing three different categories of remanufacturers namely Independent, Contract and OEM. Companies A and B are from small to medium sized enterprises whereas Company C was a large scale enterprise which has spread around the world. Company backgrounds and detailed operations are presented in the next chapter. Company A was visited with a group of four researchers on 22nd November 2012 for a half day study. Company B, was visited on 29th November 2012 again with the same group of researchers for a one full day study. Company C was not visited but a senior technical manager was interviewed within the University on 25/07/2012 and 08/01/2013 followed by an email conversation to refine the data.

3.3.3 Interviews

Interviews were conducted on site for companies A and B and offsite for company C. Interviews were semi-structured with nine areas of enquiry. These nine areas were formed to find the background on remanufacturing process of each company and to address the research question as shown in Table 6.

Interviews were conducted in two forms. First was the formal one-to-one interview in an office environment with senior technical managers to get an overall idea of the operation and industry. The second form was interviewing production staff/supervisor while walking through the production floor as observing each process of remanufacturing which made it easy to understand processes. Both modes were followed with all three companies as the exploratory nature of research and multiple disciplines of the research group visited.

Table 6: Areas of enquiry for semi-structured interviews

Area of enquiry	Used for
Number of employees	Used to identify company size and type of remanufacturer. Used especially forming Table 13 and Figure 55 : Effort/Cost of cleaning vs. factors affecting cleaning
Product types	Used to address RQ3. Which factors make cleaning more difficult/costly? and to compare in between case companies in terms of process similarities with similar product types
Sales volume	Used to identify company size and type of remanufacturer. Used especially for developing Table 13.
Cleaning methods	Used to address RQ1: Why cleaning is essential and RQ2: How much effort is required for cleaning?
Effort/Cost of cleaning	Focused directly on addressing RQ2: How much effort is required for cleaning compared with overall remanufacturing effort?
Cleaning and other process times	Focused directly on addressing RQ2: How much effort is required for cleaning compared with overall remanufacturing effort?
Difficulties in cleaning and other operations	Used to addressing RQ2: How much effort is required for cleaning compared with overall remanufacturing effort? and RQ4: What knowledge could be used to make cleaning easier and more economical?
Operating standards	To figure out any standards used for cleaning process.
Future of Remanufacturing	Again to get insights to RQ4: What knowledge could be used to make cleaning easier and more economical?

The interviews were voice recorded and transcribed for analysis. The relevant responses under each areas of enquiry mentioned in Table 6 were coded in Table 9, Table 10, and Table 11 for each company in the data analysis chapter. The responses were then used to content analysis and generating results. All four research questions were supported by data from interviews (Table 7).

3.3.4 Observations

Company A and B was visited on 22nd and 29th of November 2012 respectively. The remanufacturing process was observed from gate-to-gate. The order of remanufacturing process from disassembly to testing was followed whenever possible and field notes and photographs were taken on related processes and products. Especially cleaning processes and work in progress were captured for later reference which is included in the subsequent chapters of the thesis. Observations help to understand the complexities of products themselves and uncertainties such as core quality and ease of cleaning. Sketches were taken on the process flow which was used to develop the process flow diagrams (Figure 50, Figure 51). Clarifications were made by discussions with relevant work station personnel as and when required. There was minimal disturbance to the flow of remanufacturing process during the observation process. Observation data were used to address all four research questions as shown in Table 7.

3.3.5 Archival records

Archival records or documentary evidence were used to understand the process flows of company B. These were used to clarify the process of contract remanufacturing and developing process flow diagrams. Company D has provided the sales data for two years which were used to develop the volume and size of operation of case D. However, the nature of research does not require significant analysis of cost data especially of Case D and hence it was not discussed in greater detail.

3.3.6 Pragmatics of methods chosen

Comparison between theory and practice was an expected challenge as in any research. In the context of this research, it was critical to gain access to potential remanufacturers for observation visits. Companies operate with tight production schedules and allowing time for researchers is obviously a challenge for them. Observation visit to a production facility requires at least half a day of time and a knowledgeable person to walkthrough us and explain the system. Furthermore, significant period of time was required for interviews. As the facilities were visited as a group in most cases, the questions thrown were from various backgrounds which may hinder the quality of responses. However, those challenges were minimised by allowing extended time for planning and using University contacts for accessing the organisations.

Some sensitive areas, such as environmental initiatives and in-house innovations of customised tools and techniques were also a challenge during data collection. Despite the companies were helpful more than expected, the sensitive areas had to be treated with care acknowledging their concerns. This also may have caused a very marginal impact on the quality of data collected using observation and interview methods.

Table 7: How to address the research questions

Research question		Literature survey		Case study		
		Remanufacturing	Product cleaning	Direct observation	Interviews (Semi-structured)	Archival records
1	Why cleaning is essential in products remanufacturing?	×		×	×	
2	How much effort is required for cleaning compared to overall remanufacturing effort?	×		×	×	×
3	Which factors make cleaning more difficult/costly?	×	×	×	×	
4	What knowledge could be used to make cleaning easier and more economical?	×	×	×	×	

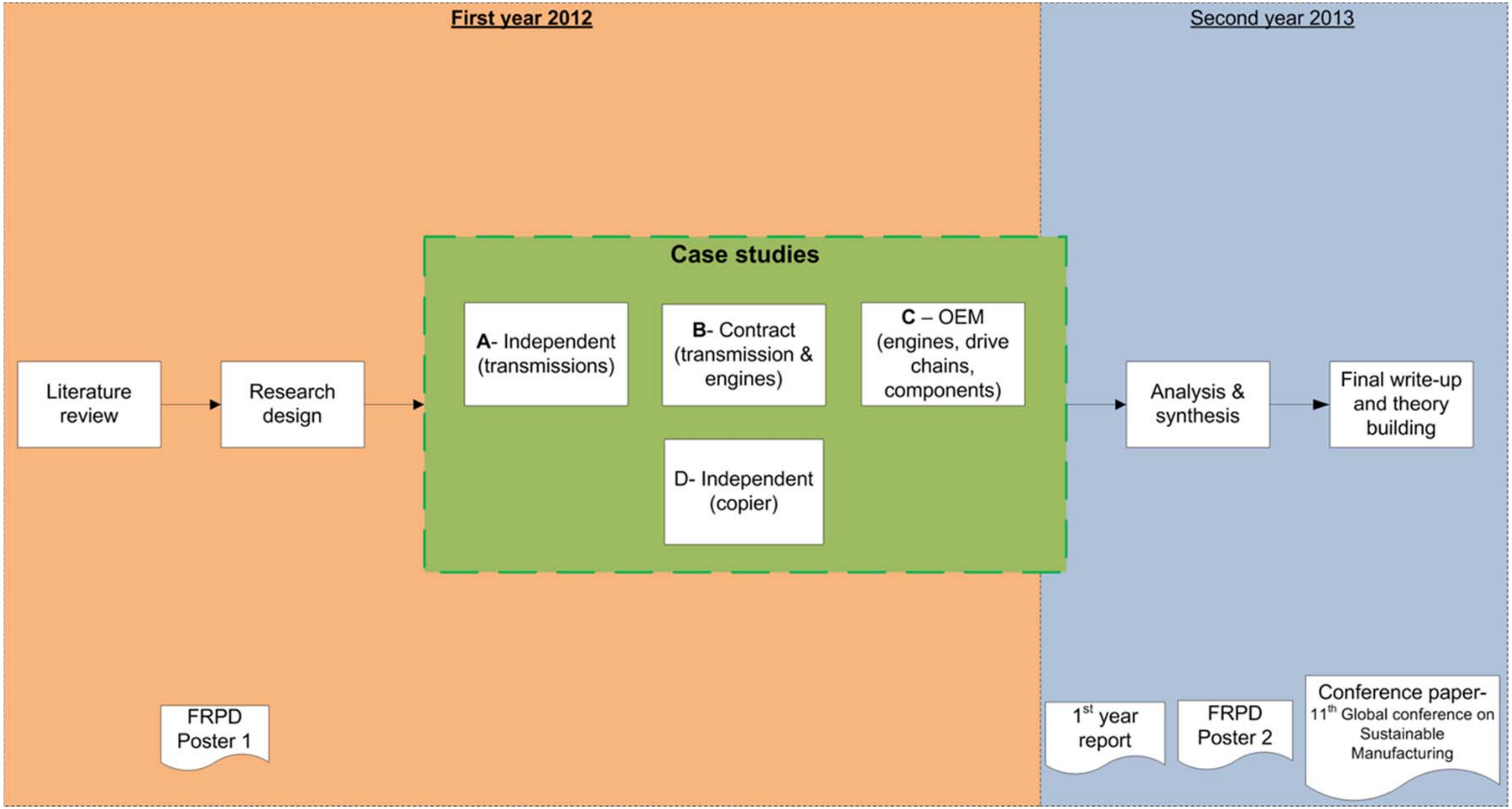


Figure 16: Research Plan

4 INDUSTRY CASE STUDIES

Three automotive remanufacturing companies and one photocopier remanufacturer in the United Kingdom were selected for the study. Criteria for selection of companies were presented in the previous chapter, section 3.3.2 How the case studies were conducted. Senior technical managers and operational level staff were interviewed onsite. Senior technical managers were chosen to interview as they have the overall picture from beginning to end of the remanufacturing process, which makes it easier to compare in between processes, especially cleaning. Further, they have a better understanding on how the supply chain operates and better identify the issues and stakeholders in the industry. Operational level staff was chosen as they could identify specific technical issues of each process of remanufacturing that they are familiar with. So these two groups were well suited to answering research questions. Direct observations and company documents were used to understand the process and relevance of cleaning in particular. The entire process of remanufacturing from gate-to-gate was observed during case study visits to understand the overall process and specifically to have an idea of the relative importance of cleaning among the other steps.

4.1 Company A

Company A is an independent remanufacturer in the UK which is involved with the business of automotive remanufacturing. The company was founded in 1977 as a family business. They undertake remanufacture of both automatic and manual transmissions in passenger vehicles and light duty goods transfer vehicles. Now it has grown to SME level employing around 25 skilled workers with a state-of-the-art remanufacturing facility. It serves leading brands, including Hyundai, CAT Logistics, Nissan, Chevrolet, SsangYong, Subaru and several other industrial partners. Their sales figures amount to 600 units per year, which may vary greatly depending on the annual demand. They also maintain good-quality levels within their operations and are accredited with the ISO 9001:2008 quality standard. The main components that they are dealing during remanufacture are hydraulic control units/valve bodies (Figure 17) and torque converters (Figure 18) which are integral parts of an automatic transmission.

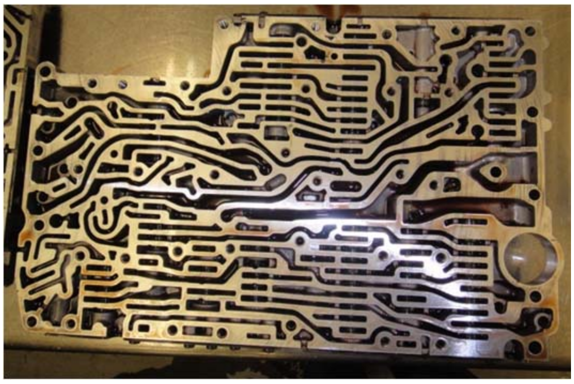


Figure 17: Valve body (key part of hydraulic control unit)

Figure 18: Torque converter (“www.anjomachine.com,” 2013)

Being an independent remanufacturer has its own advantages and disadvantages. Their well experienced professional staff with 15-20 years of experience in remanufacturing is the key strength of the company. Furthermore they have built up a good company image over the years by serving individual customers with user friendly and reliable service. Apart from the human capital, they have invested in state-of-the-art testing facilities for valve body testing and transmission testing. The process flow diagram is included under results section (Figure 50) for ease of comparison with other case studies.

4.1.1 Disassembly in company A

The remanufacturing process within company A is illustrated in Figure 50. The process is explained with respect to remanufacture of an automatic transmission. First, the received cores are cleaned from the outside to facilitate disassembly. The process is carried out one unit at a time as it is a small-scale operation. The core is disassembled regardless of any fault. Separate work benches are provided facilitating disassembly. It is a fully manual process though sometimes aided with machines. After disassembly there could be three main parts, namely the transmission itself, i.e. the gear wheels, shafts and housing, valve body or the hydraulic control unit and the torque converter. For stripping the torque converter, special tooling is required to grind off the welded joint in the centre. After stripping, the components are sent for cleaning.

4.1.2 Cleaning in company A

In cleaning disassembled gears, valve bodies and torque converters they are initially subjected to a machine wash. The machine washes several times with degreaser chemicals and water which would take about an hour to clean fully for a transmission. The design of the cleaning machine is quite simple and similar to a dish washer. A set of spray nozzles sprays the cleaning liquid at high pressure from the bottom, while rotating. The components are placed above these nozzles on a wire mesh facing the required side of the component to be cleaned. This may take some time and require manual rearrangement or re-orientation of components to get all sides cleaned.

However, due to intricate shapes and tough debris of components, manual cleaning is also required in some cases to achieve the required level of cleaning. This may take excessive labour hours apart from the machine hours spent.

4.1.3 Inspection in company A

Inspections are being done in several stages of component testing. The torque converter testing is done mainly with visual inspection. However, for the valve body there are a couple of tests involved, a vacuum test (Figure 19) for the valve body itself and a separate inspection of the solenoids using a dedicated solenoid flush and test machine (Figure 20).

Figure 19: Vacuum test for valve body

Figure 20: Solenoid flush test unit

The valve body is considered to be one of the most complex parts in an automatic transmission. Cleaned valve bodies are tested with a vacuum test to examine any worn-off bores or cracks. Each bore of the valve body is subjected to around a negative 15 bars of vacuum pressure. If it can hold that amount of negative pressure it is decided that the bore is satisfactory. If the bore is worn then it will not be able to hold that negative pressure. In such cases an oversized valve is used after reaming it to the new valve diameter. The oversized valve and the reamer are sourced from a specialised supplier. According to the interviewee, one of the most difficult parts to remanufacture is the valve body. This is due to the size and delicacy of parts like small springs, solenoids, complex shapes and thinner walls of the valve body itself. Sometimes a miniature crack in a wall may allow oil to be by-passed at high operating pressures and temperatures, but be very difficult to locate.

4.1.4 Testing in company A

Testing is carried out at sub-assembly level and finally for the full assembly of the automatic transmission. The assembled valve body is tested in a dedicated machine (transmission shifter test machine Figure 21) for pressure developed for each gear. The pressure versus gear position graph is matched with the OEM specified graph and a final decision is made about the quality of the remanufactured hydraulic control unit. Then it is sent for final assembly of the transmission.

Figure 21: Transmission shifter test machine

The final full assembly, transmission, hydraulic control unit and the torque converter, is tested in another test rig (Figure 22) for no-load and load conditions in each gear. Loading is done by an electromagnetic loader and the unit is powered by an electric motor. The performance is viewed in the test display unit and compared with OEM specifications. The final decision is then made for successful remanufacturing.

Figure 22: Final assembly test unit

The final product is then painted, labelled and sent to the finished goods section.

4.2 Company B

Company B was founded in 1960s as a metal fabrication company and major development into remanufacture was initiated in 1978 with a contract for Ford motor company. The company serves popular brands in the automotive industry, Ford, General Motors, Volvo, Mitsubishi, Jaguar and Land Rover. Company B produces around 75% of its sales by remanufacturing manual transmissions. The second in line is engines which contribute around 12% of total sales. The rest is formed out of transfer cases, differentials and non-automotive products. Company B is categorised as a contract remanufacturer as they are under a contract with an OEM to remanufacture their products in batches. The company currently employs 75 personnel in a relatively large (medium sized) remanufacturing facility in UK. The company produces around 15,000 units a year on average. The production is made-to-order from the OEM, who is the sole supplier of cores and the customer of remanufactured units. Company B does not have a direct involvement with the individual customer, so it operates mainly in a B2B environment. They maintain high quality standards to comply with their customers' quality expectations and brand image. They are awarded with ISO/TS 16949:2002 and ISO 14001 standards. Further an intra-company standard within Ford, named 'Ford Q1', is also among those certifications.

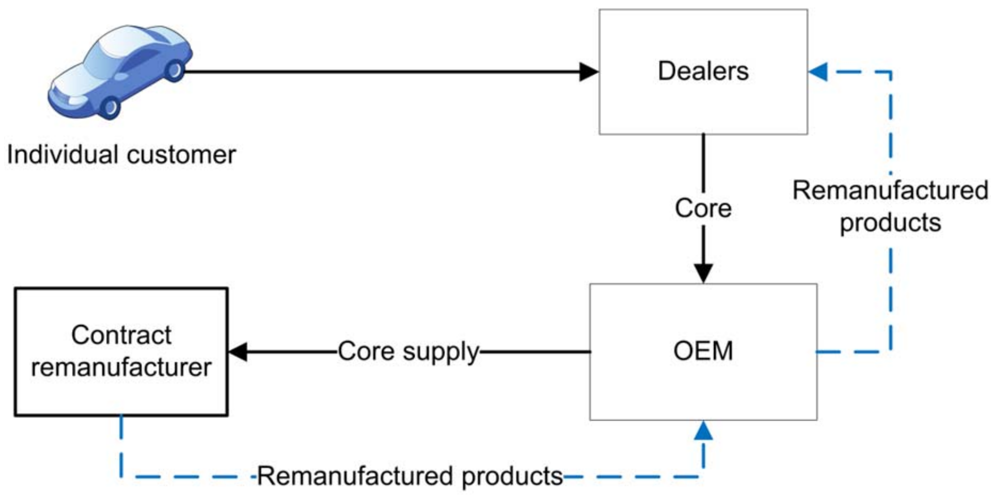


Figure 23: Business model of Company B – a contract remanufacturer

The business model of how company B operates could be illustrated as in Figure 23. The OEM collects the cores from vehicle dealerships and returns remanufactured products to them. There is little interaction directly with individual customers and OEMs in the automotive passenger vehicle industry unless the customer is a large fleet operator. The interface with individual customers is normally formed by the vehicle dealerships. The cores are collected and kept in stock within OEMs and orders are placed depending on the demand from dealerships. Cores are received in batches for the OEM to company B and they keep those in a warehouse until an order is placed. The main components they remanufacture include manual transmissions, engines, transfer cases and differentials.

Figure 24: A Manual transmission ("http://www.mustangandfords.com/," 2013)

Manual transmissions (Figure 24) are the most common mode of transmission. It is much less complex compared with an automatic transmission of a similar vehicle model. It contains a clutch instead of the torque converter in an automatic transmission. Also it does not have a complex hydraulic control unit including valve bodies and solenoids, but a simple lever mechanism to manually shift the gears.

Figure 25: Transfer case (“www.uneedapart.com,” 2013)

Figure 26: Front differential of a Ford Sierra (“www.super7thheaven.co.uk,” 2013)

Transfer cases (Figure 25) are used in four-wheel drive vehicles. It transfers power from the transmission to the front and rear wheels. It is placed between the transmission and the front and rear axles, transferring power through two drive shafts. The differential (Figure 26) could be there either in two-wheel drive or four-wheel drive vehicles. The function of the differential is to facilitate the difference in speeds of each wheel when taking a turn while transmitting the power from the transmission. Both of these products contain gear assemblies inside which need to be dismantled to part level during remanufacture.

The process flow of company B in the context of remanufacturing of manual transmission is illustrated in Figure 51. The cores are stocked in their own warehouse which is situated close to the remanufacturing plant but still dispersed. The warehouse holds roughly 20,000 units at any given time which is a little higher than an average year’s production. Once an order is received from the customer, i.e. OEM, the relevant product cores are selected and transported to the remanufacturing site. The process flow diagram is shown under in Figure 51 of Results section for ease of comparison and discussion.

4.2.1 Disassembly in company B

The first step is to strip the core into parts after cleaning any external dirt as in every remanufacturing process. The disassembly process is mainly manual, but there are custom-made tools like hydraulic bearing or gear pullers (Figure 27) to assist and speed up the process. Disassembly takes around 25 minutes on average for one manual transmission by a single worker. The process is more organised than in Company A as company B is practising lean manufacturing principles to a considerable extent. That is evident from well-designed custom made carrier trays (Figure 28) to fit the components of each model of transmission. These are made out of metal wires and facilitate the easy and orderly stacking of parts in the tray. This could be considered as a pre preparation for the following processes of remanufacturing too, as these trays are directly transferred to cleaning machines and up until reassembly stage.

Figure 27: Custom made hydraulic pullers

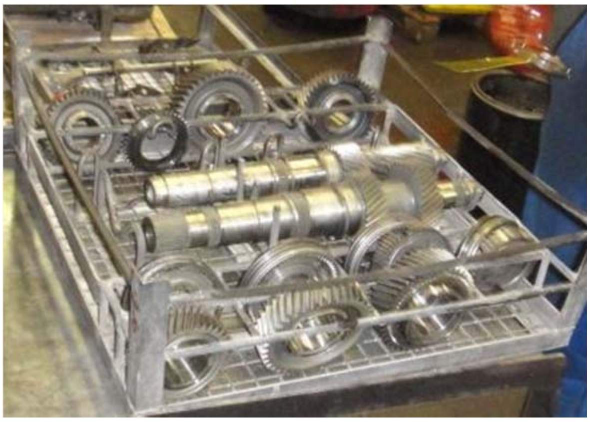


Figure 28: Parts carrier tray

During disassembly, all the compulsory replacement parts like bearings, gaskets and oil seals are discarded. The remainder which are worth cleaning and inspection are sent through a conveyor for subsequent processes.

4.2.2 Cleaning in company B

Company B uses a variety of machines and methods to clean the disassembled parts. From the disassembly section all parts, except the casing, come to the cleaning section stacked in a metal carrier tray (Figure 28) through the conveyor. The transmission housing/casing comes separately. There are five main types of cleaning processes being used in company B.

4.2.2.1 Cleaning using Kerosene (Submerged)

A gear box is full of lubricant during operation to lubricate gear mating points and to absorb the heat generated during operation. Once dismantled, every component is full of burnt oil. To remove this oil and grease sediment, kerosene is used. The first process in cleaning is to agitate the components with the container trays, dipped in a kerosene bath. These kerosene washers remove black burnt oil and grease sediment. However, following the process all components have kerosene residue (Figure 30) and other stains which do not dissolve in kerosene. This leads to a secondary washing process.

Figure 29: Kerosene washer tank

Figure 30: Oily components just after kerosene wash

4.2.2.2 Aqueous based chemical cleaning (Submerged and Spray)

Aqueous-based chemical cleaning could be done in two machine arrangements. One arrangement is that the parts are submerged in a tank full of cleaning liquid and agitated by a vertically reciprocating platform. The other method is by pressure spraying the cleaning liquid on the parts to be cleaned.

In both arrangements the parts are stored in a platform inside the machine with the carrier tray itself. Storing of the trays is done manually either by pushing it on a roller conveyer or using an electric hoist support. Once the machine is securely shut to avoid any leakage of liquid, the internal platform with part trays reciprocates up and down. The platform with part trays is submerged in the cleaning liquid allowing the liquid to agitate through the parts. This agitation inside an aqueous-based chemical cleans the parts to a much greater extent removing kerosene and any residual lubricant oil, debris and carbon stains.

Figure 31: Aqueous-based chemical washer for transmission housing

The cleaning of the gear wheels and housing is done in two separate washers. The reason for this is that the chemicals used for cleaning gearwheels and the other steel components cannot be used for aluminium casings. This is because it will react and decay the aluminium material. So a different aqueous based chemical is used in a separate washer to clean transmission housing (Figure 31). The washer may be designed for a submerged arrangement or a spray cleaning arrangement. The operating temperatures inside these cleaners may vary from 70 – 85 °C.

Figure 32: Components before cleaning

Figure 33: Components after cleaning

Figure 32 shows a picture of a container of oily transmission components queued up for the cleaning machine. Figure 33 shows a similar container of components after cleaning from both kerosene and aqueous-based chemical cleaners. The shiny oil free surfaces can be seen in that tray.

Figure 34: Spray cleaner inside view

Figure 34 shows an entry viewpoint of a spray-cleaning machine just after kerosene washing. In the centre just below the conveyor rollers the spray nozzle with the tube can be observed. There could be two or more spray nozzles depending on the machine type. Spraying is started once both entry and exit doors are shut. Then cleaning components are ready to be sent to the inspection point after drying with an air gun.

4.2.2.3 Manual cleaning with brushes

Machine cleaning with both kerosene and aqueous chemical spray, cleans components to a great extent. However, some product or parts with intricate shapes are not cleaned enough for remanufacture. These intricate areas of a component have to be cleaned manually as shown in Figure 35.

Figure 35 : Manual cleaning of transmission housing

A degreaser liquid (parathane/kerosene) is used with a wire brush to achieve the required level of cleaning. This requires a considerable amount of labour hours as opposed to the machine hours spent on cleaning.

4.2.2.4 Shot blasting

Shot blasting is another method of obtaining a cleaned/polished surface especially in transmission and engine housings. The OEM, the customer in this case, requires the remanufactured products to be finished to the same standard as the new product. Shot blasting gives a real material (Aluminium or Steel) appearance to the remanufactured component compared to a silver colour spray painted component. Company B uses shot blasting as a method in cleaning transmission housings. The component material is mainly aluminium. A shot blasting machine in operation is shown in (Figure 36). The operator loads the component to be shot blasted and watches through a viewing window. The operator can inspect and change the orientation of the component using the access gloves built-in to the machine itself.

Figure 36: Shot blasting machine

Figure 37: Rinsing of residue after shot blasting

Once the blasting process is finished the residual blasted powder material should be washed away manually. This is another manual-washing process (Figure 37) which again increases the manual labour hours. The washing is done within the machine itself to recover the substance used.

4.2.2.5 Vibration cleaning

Some parts of the transmissions and engines such as gear wheels, piston heads, etc. require the mating surfaces to be thoroughly cleaned and polished. The smooth surface finish is required by the nature of the operation which normally is designed to minimise friction. This is done through a vibration cleaner (Figure 38). The parts to be cleaned are put in to a bowl of grits and vibrated while rotating within the grit mixture. The relative motion of the grit with the components cleans and polishes the metal surfaces giving a very smooth surface finish (Figure 39).

Figure 38: Vibration cleaning/polishing machine

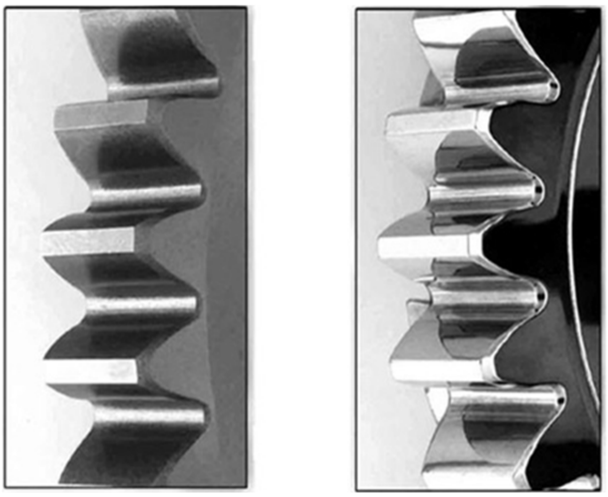


Figure 39: Before and after component cleaning/polishing ("http://www.rosler.com/," 2013)

Company B spends around 40-60 minutes on the cleaning operation for one transmission. This amounts to 1/3 of the total remanufacturing time spent of three hours. This is mainly due to manual cleaning operation rather than machine cleaning operation. This is due to the ability of machines to accommodate several units at a time.

4.2.3 Inspection in company B

Once the components are cleaned to the required degree, they are transferred to the inspection section within the carrier tray itself. Visual inspection is prominent and hardly any machines used for the transmission inspection. The process is mainly driven by the trained and experienced inspector. There are around seven employees trained on inspection but there is only one or two working at a time on the transmission line. Others are allocated to the engine remanufacture line. Assistive tools like surface gauges, magnifying glasses are used (Figure 40). A guide manual is available which is developed by the company's engineering team to guide the inspector on making the decision with visual samples.

Visual-management techniques in lean manufacturing have been used to a considerable extent within company B. One more such application is the new padded container (Figure 41) for each model of transmission. This container has an empty slot for each and every component in the transmission. There are carrier trays designed for each and every type of transmission they undertake to remanufacture. The inspector checks each and every component and puts them back in the relevant slot if suitable for reuse. Parts that are not suitable for reuse are scrapped and replaced with new parts from the inventory.

Figure 40: Visual inspection of a gear

Figure 41 : Container to arrange the components for assembly

The inspection is looking for any worn or deformed gear teeth, mating grooves, key ways, couplings and synchronisers. The shafts are also inspected for bending, other surface irregularities and for straightness using level gauges.

4.2.4 Reassembly in company B

Once the inspection is done, the container with all required components for one particular transmission model is passed to the assembly area. There are two workers working at a time in assembling a transmission. Electric hoists are also used to lift and orient heavy items (Figure 42) during assembly. Electric bearing pushers (Figure 43) are used to mount the gear wheels and push fit bearings on to the main shaft. Custom-made jigs and fixtures (Figure 44) are used to assemble the subassemblies before mounting on the actual gearbox housing. These are designed to suit one particular model of transmission and are usually made out of Teflon.

Figure 42: Electric hoists used during re-assembly

Figure 43: Electric bearing pusher

Figure 44: Fixtures used for assembly

Heating and cooling of components are used to achieve thermal expansions and contractions which facilitate the fixing of components to the shaft.

4.2.5 Testing in company B

The manual transmissions are tested for load and no-load conditions. This is done using a dedicated testing rig (Figure 45) as in company A. The transmission is first run under no load for each gear. If there is no uncommon or strange sound or vibration in operation then it is tested for loaded condition. The loading is modelled by applying a static breaking torque of around 40 Nms. Each gear is tested again for a loaded condition. The sound of the operation is the main parameter to decide on the test. The transmission oil is removed after the test as the remanufactured transmission is sold without transmission oil in it.

Figure 45: Testing a manual transmission

Successfully-tested transmissions are labelled with a traceability code and sent to the finished goods warehouse.

4.3 Company C

Company C is an OEM remanufacturer with more than 30 years of remanufacturing expertise. The remanufacturing unit of the company undertakes remanufacture of medium- to heavy-duty machinery. Its current remanufacturing line caters for over 6,000 products including diesel engines, drive chains, fuel systems, hydraulics and many more. The operations are spread all over the world amounting to 17 remanufacturing facilities, but the UK-based facility employs around 300 employees who are dedicated to remanufacturing. It undertakes the remanufacture of engines (mostly diesel), transmissions, gearboxes, oil pumps, water pumps, cylinder heads, cylinder packs and individual engine components, such as connecting rods. Being an OEM remanufacturer they have full access to the technical information of each and every component. It also has control over the aftermarket and intellectual property. They offer a fixed price for the aftermarket products through dealers irrespective of the quality of cores. The remanufactured products are sold to three types of customers, fleet customers, small-volume customers and single unit users. Whatever the type of customer, remanufactured products offer them good value for money compared to the price of a new product.

4.3.1 Cleaning in company C

A senior manager in remanufacturing operations was interviewed, outwith the premises, regarding the cleaning operation used during remanufacturing. They use several cleaning methods including chemical baths, shot blasting, soda blasting, vibrational cleaning and manual cleaning. There are a few key points noted with regard to the cleaning operation during remanufacture.

Company C markets not only whole remanufactured products but also individual components. The component remanufacture is for spare parts for maintenance offering a cheaper but trustworthy alternative to the newly-manufactured counterparts. For example, a piston of an engine could be remanufactured to be marketed as a component at the same time as part of a whole engine remanufacture. Company C uses a variety of cleaning techniques, including vibration-glitz cleaning, spray cleaning and manual cleaning. It was found that research is going on to find out new cleaning techniques in a foreign branch, investigating the use of ice crystals for removing carbon deposits from components during remanufacture. However, this has yet to be implemented at commercial level.

Several factors affecting cleaning cost were identified during the interview. First is the type of material. Ferrous-based materials are easy to clean with the cleaning technology available and disposal of the residues are not that costly. However, when it comes to aluminium cleaning, the chemicals used are highly expensive and it is very costly to dispose of them complying with environmental regulations. This is an added cost to the total cleaning operation as a considerable volume of components are made out of aluminium. Not only is there steel and aluminium, but also a variety of materials being used in today's machines including a lot of plastic-based materials and brass. The higher the variety of material types, cleaning becomes more difficult as there are complexities with cleaning methods and the chemicals being used. It was mentioned that consumables of cleaning alone accounts for 10% of the total cost of remanufacturing in company C. This is excluding any labour hours or other factory overheads. This figure was given as a reply to the question on the proportional cost incurred for cleaning only during remanufacturing as it is very hard to calculate as the remanufacturing operation is too complex.

Another major factor that causes extended cleaning time is the nature of output or the market form of products. It specifically mentions 'what is good enough cleaning?' which is vague during the practical life of remanufacturing. By definition, products should be restored to like-new performance. But the same component may undergo two different processes of cleaning due to the market form of it. For example, a piston in a diesel engine could be cleaned and remanufactured to be sold in the component form itself or it could be cleaned as part of the remanufacturing process of the whole engine. In the first case, appearance of the component matters a lot when a customer compares a new piston to that of a remanufactured one. But when it comes to whole-engine remanufacture the comparison is not that critical. In this example, the piston may undergo additional cleaning and polishing operations during remanufacture than during whole-engine remanufacture. This is a sensitive area under discussion as one may ask whether it is possible to put less cleaned components inside the engine and assemble it making only the outward appearance look new. The answer would be 'no' because to offer the matching warranty on the new counterparts technically there is an essential amount of cleaning to achieve the like-new performance of the product. This is a factor that was not found either in company A or B as they are mainly in the business of whole product remanufacture.

One more concern is the disposal of cleaning waste. The effluent may consist of cleaning waste and some environmental regulations specify strict procedures for disposing of some hazardous substances. For example, the chemicals used to clean aluminium components.

These need to be processed through special treatment processes which cost additional overheads and labour hours. This work is in addition to the normal effluent treatment processes for treating general factory waste using aerobic and anaerobic digestion. Being a large scale OEM, the volume of hazard emissions, both liquid and gas, to the environment is high. These need to be well attended and treated to comply with environmental regulations, which left OEMs with an added burden. This in turn contributes to the cleaning costs of remanufactured products making them expensive in the market, whereas for SME level operators those emissions are small compared to OEMs. SMEs accumulate the used hazardous material in containers and dispose of it through licenced contractors. They are disposing of the waste in their facilities according to regulated guidelines. This left SME level remanufacturers with a lower cost for disposal of cleaning effluent per product thus making their cost of production lower. Therefore, compliance with the environmental regulations by insourcing could be considered as another factor that increases the cost of cleaning during remanufacture for OEMs.

4.4 Company D

Company D is completely different from the rest of the three companies as they remanufacture photocopiers. The key reason to consider Company D is to compare the importance of cleaning operation within automotive remanufacturing with that of another industry. Photocopier remanufacturing is a key industry contributing a larger portion of the remanufacturing industry. Case D will briefly discuss the cleaning operation to understand how significant is cleaning within copier remanufacturing. This will help compare the efforts put towards cleaning among automotive and copier industry.

Company D could be categorised as an SME-level independent remanufacturer. The company commenced its remanufacturing centre in 1994 as a life-extension programme for copiers. They operate with approximately 15 employees and remanufacture around 400 units per year. The company remanufactures copiers on demand from the individual customer and also remanufacture to stock. Made-to-stock remanufactured copiers are then marketed and sold through city offices all around UK. The production manager of the company was interviewed on-site regarding the remanufacturing process.

4.4.1 Cleaning in Company D

The disassembled units are then cleaned manually with an air-gun to remove dust (Figure 46). No machine cleaning is involved as with automotive remanufacturing. The panels are then washed manually by aqueous chemical liquid and dried.

Figure 46: Cleaning a copier panel with an air-gun

Cleaning is not a k for company D as there is not much dirt or debris accumulated as with automotive parts. Only one operator is allocated for the cleaning operation. It will approximately take two days to fully remanufacture a photocopier of which a little fraction of time is spent on cleaning with a low skilled worker. One more reason for less effort in cleaning is that the plastic panels are spray painted at the end to achieve a like-new appearance.

In conclusion, it can be seen that the scope for cleaning, both time and cost wise, within copier remanufacturing is far less compared to automotive remanufacturing. However, Company D is achieving the functional and appearance performances of the product complying with the remanufacturing definition. Thus it can be ascertained that cleaning during automotive remanufacturing is much more important to achieve proper standards of remanufacturing. The process flow diagram of company D is presented in the Appendix.

4.5 Summary of case companies

There were three automotive sector case studies and one photocopier remanufacturing study. The case studies covered all types of remanufacturers, independent, contract and OEM. The step-by-step remanufacturing processes in each company were studied and summarised in Table 13 in the results chapter. The table provides an overall picture of the backgrounds of each company and what each company does during the remanufacturing process.

The attention to cleaning was comparatively low in company A, medium in Company B and high in Company C. This is because an OEM has to strictly comply with environmental regulations and with its own standards. The use of cleaning technology also increased from company A to C as the volume and complexity of operation increased. Furthermore company C has to make an extra effort with cleaning as their output products include remanufactured spare parts as well as whole units.

5 DATA ANALYSIS

Gathered data can be categorised in to three main forms. These are data from academic and trade literature, data from observation in the form of photographs and field notes, and data from interview voice records/emails. These data were analysed using various tools and techniques described below.

5.1 Content analysis using NVivo

The data found from academic and trade literature was coded in NVivo 10 which is well referred qualitative data analysis software. The content analysis process was carried out to identify research themes, trends and research gaps. The software tool was used to analysing and generating results from qualitative data from literature and case studies. Figure 47 shows a screen capture of NVivo interface showing themes under which the data were coded.

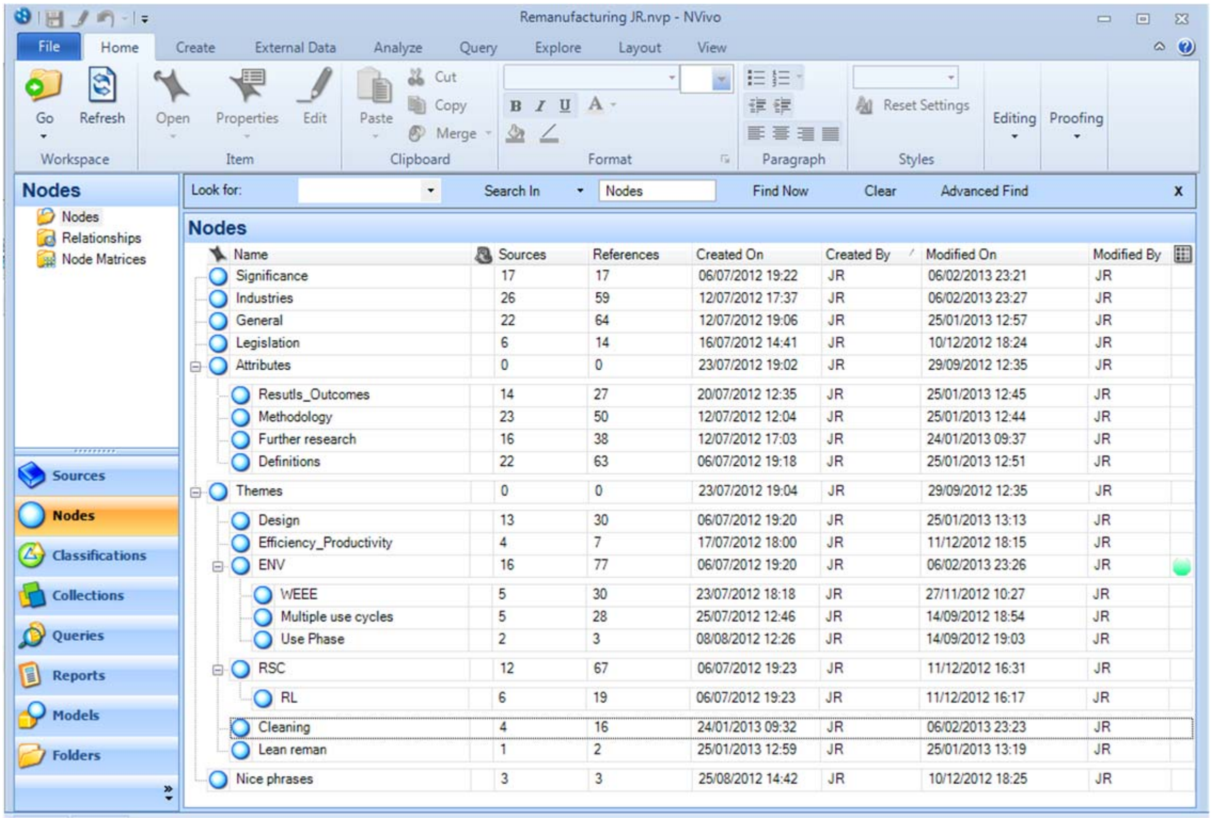


Figure 47: Thematic coding using NVivo 10

The meanings of coded themes are briefly explained bellow. The term '*Node*' referred here is the term used in NVivo to identify the containers of thematic coding.

- **Significance** – This node is coded with data that specifically emphasise the importance of automotive remanufacturing. The theme was intended to cater the introduction of thesis and developing the story of necessity of remanufacturing to the reader.

- **Industries –** This node was formed to ascertain the key industries which are into remanufacturing and how important automotive industry among them.
- **Genera**l **–** the general node comprise non-specific data which cannot be coded under any other node yet relevant to the research. An example would be a categorisations made by a previous researchers on end of use strategies.
- **Legislation** – This contains the records on legislation that influence the end-of-use products. This includes directives such as end of life vehicle directive (ELV), Waste Electrical and Electronic Equipment Directive (WEEE), Restriction of Use of certain Hazardous Substances Directive (RoHS), and the Packaging and Packaging Waste Directive.
- **Attributes** – Attributes node has four child nodes facilitating coding of key information of sources referred. These were mainly developed by
    - Results/outcomes – This contains outcomes mentioned in previous research studies leads to help identify the state of the art in remanufacturing research.
    - Methodology – This comprises the methodologies adopted by previous researchers. This node was the main source used to develop the Table 16: Analysis of methodologies adopted by previous researchers.
    - Further research - This node was used to identify the research gaps and directions indicated in the previous research which was used to formulate the gaps mentioned in the literature review section.
    - Definition - The key definitions of end-of-use strategies were coded from various sources within this node and analysed and presented in the first part of literature review. This has been used to form the key sections in the introduction section when answering the questions ‘What is remanufacturing?’ and other end-of-use processes.

The next set of nodes was coded under major themes identified in remanufacturing literature. As can be seen from Figure 47 these themes are design for remanufacture, efficiency or productivity of remanufacture, environmental impact assessments associated with remanufacture, reverse supply chain and reverse logistics, cleaning within remanufacturing and lean remanufacturing. A 'source' referred in the Figure 47 could be any data source such as a journal paper, memo, or transcribed interview or interim report. A 'reference' means a piece of data coded from a particular source. Therefor one source may contain many references. When a particular node is opened the references from all the sources can be viewed as shown in Figure 48.

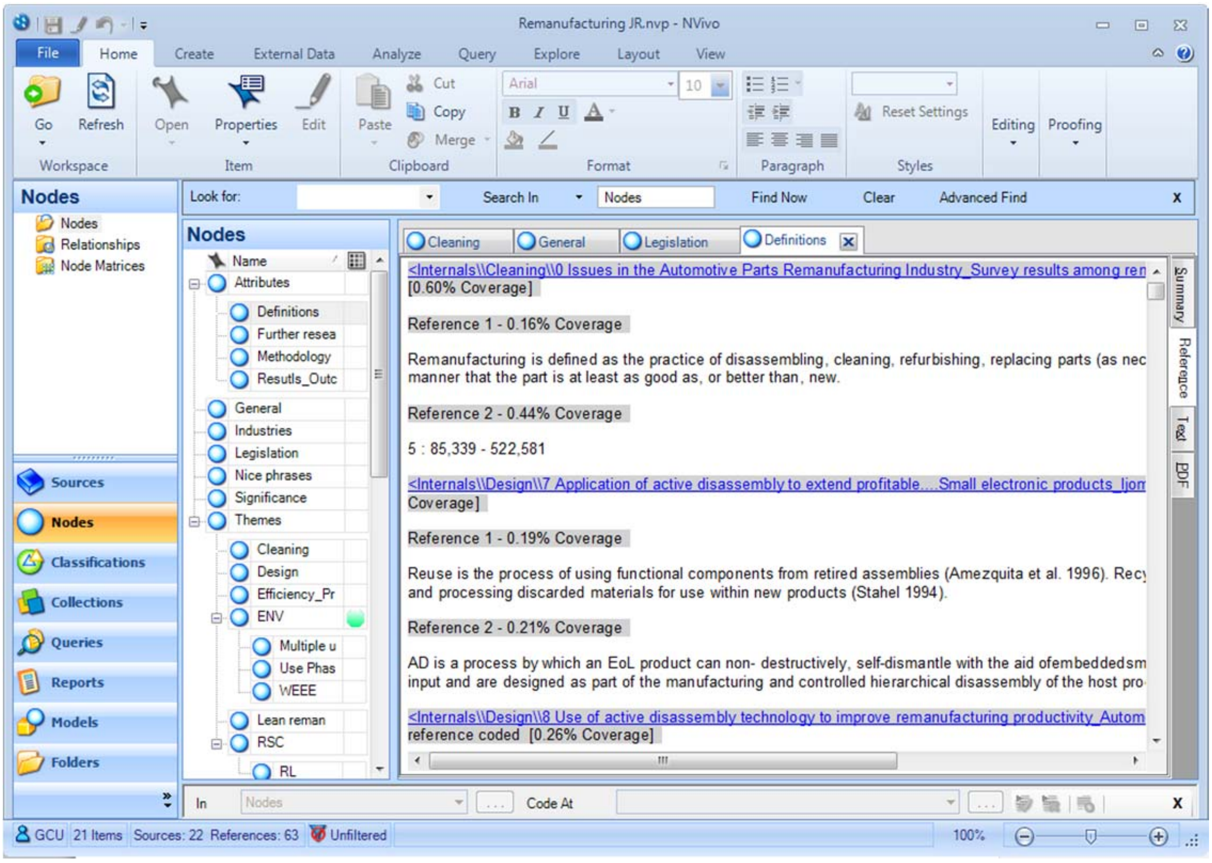


Figure 48: Exploded view of the node - 'Definitions'

The figure shows the exploded view of the 'Definitions' node and how various data sources are coded into a one node. This gives quick and easy access to the definitions when drafting the thesis chapter 1.

5.2 Interview responses analysis

Interviews were semi-structured to ensure the objectives are met and to appreciate the variations of companies. The interviews were voice recorded during case study visits except for company C for which two interviews were followed by series of emails to clarify issues. The voice recordings were then transcribed and coded to relate relevant research questions. The duration of voice recordings for company A was 1:57 hours, and for company B it was 4:24 hours.

Table 9, Table 10 and Table 11 present structured extracts from interviews, emails, field notes and web sources which are relevant to address the research questions. Due to the sensitive nature of data and anonymity, some texts have been removed from the quoted responses to maintain confidentiality. The responses were categorised under nine areas of enquiry in the evidence table (Table 8) which is a duplication of Table 6 of research methodology section for ease of reference.

Table 8: Structure of evidence table showing how to address research questions

Area of enquiry	Used for
Number of employees	Used to identify company size and type of remanufacturer. Used especially forming *Table 13: Comparison of companies and Figure 55 : Effort/Cost of cleaning vs. factors affecting* cleaning.
Product types	Used to address RQ3. Which factors make cleaning more difficult/costly? and to compare in between case companies in terms of process similarities with similar product types
Sales volume	Used to identify company size and type of remanufacturer. Used especially for developing *Table 13: Comparison of companies*
Cleaning methods	Used to address RQ1: Why cleaning is essential and RQ2: How much effort is required for cleaning?
Effort/Cost of cleaning	Focused directly on addressing RQ2: How much effort is required for cleaning compared with overall remanufacturing effort?
Cleaning and other process times	Focused directly on addressing RQ2: How much effort is required for cleaning compared with overall remanufacturing effort?
Difficulties in cleaning and other operations	Used to addressing RQ2: How much effort is required for cleaning compared with overall remanufacturing effort? and RQ4: What knowledge could be used to make cleaning easier and more economical?
Operating standards	To figure out any standards used for cleaning process.
Future of Remanufacturing	Again to get insights to RQ4: What knowledge could be used to make cleaning easier and more economical?

Table 9: Analysis of interviews, field notes and email responses – Company A

Area of enquiry	Responses (Interview and Field notes) – Company A
Number of employees	Less than 25 (Field notes: 22/11/2012)
Product types	Automatic transmissions and manual transmissions (Field notes: 22/11/2012)
Sales volume	Approx. 600/year (Field notes: 22/11/2012)
Cleaning methods	*"....then again it (Dismantled parts) gets to washing machine, that is the unit came with…… definitely that material will be washed, again same principle this quick .. dishwashers are capable….at this point its cleaned and we've all the parts laid down (for inspection)"* (Audio file - 01:04/1:57:00) Ones cleaned the transmission cases are spray painted (Field notes: 22/11/2012)
Cost of cleaning	*Q: " In terms of cost, what is the biggest in remanufacturing?"* *A: " I'm not sure because the time card in there, they work the costs out in the office, they gets the guys' time cards and …. I am not sure.."* (Audio file - 52:50/1:57:00)
Cleaning and other process times	*Q: "how long this (test of automatic transmission) run for?"* *A: "as long as we need….you know transmission got certain programme to run, you can run it and change the pressure move around to find a problem…so we can run it for 5minutes, over an hour"* (Audio file - 15:22/1:57:00) *Q: " How long it will take to disassemble all these (automatic transmission)?"* *A: " disassemble this?., probably about an hour... maybe not even an hour, …….may be another hour to wash it and clean it..and probably 6-7 hours to rebuild it..* *Q: " so you can turnaround that transmission under 24 hours?"* *A: " Ooo aaay, yes, it can be done in a day…strip, wash, and rebuild, in a day"* (Audio file - 43:52/1:57:00)

Difficulties in cleaning and other operations	*Q: "I suppose it is the same detergent used for washing, so there is no point of separation?"* *A: "yeah, same stuff (detergent), put all (parts) in one machine (cleaning)……..automatic transmission is got to be spotlessly cleaned which is not so important in a manual transmission"* *Q: "So does that mean that they have different cleaning requirements..?"* *A: "No, but we use the same cleaning….obviously we do the manual the same way we do the automatic...but it is not the manual which need the better cleaning, it need to be spotlessly clean to rebuild the automatic, because if you got a one bit of dirt in that transmission, when you are rebuilding that, it cause all sources of problems in that valve body there.. that valve body will be stripped down so there is nothing left in there and we'll clean that and inspect it make sure all the valves are ok. Springs are ok…."* (Audio file - 41:55/1:57:00) *Q: "What is the most difficult thing you find about remanufacturing?"* *A: "the most difficult part to remanufacture is the valve body, the valve body is the most difficult thing to do in the automatic transmission , just because it holds valves, springs, then you got solenoids in there as well,…if the oil is leaking from pone channel to the other channel transmission not going to perform correctly"* (Audio file - 17:03/1:57:00) *Q: "Most of the cars come with electronics components and it's going to be higher in the future. So as an automotive remanufacture you got to be able to deal with these electronic components. What do you think about that?"* *A: "I don't think you need to remanufacture the electrical components, because you can buy some of the electrical components,…..if we got a transmission to remanufacture and if that transmission got solenoids in it we need to replace them, because solenoids are little magnets …..Opening up a solenoid and cleaning it out doesn't say it is going to work, buy the solenoid, we could send that transmission 300 miles away and we've got a problem if that guy(customer) says it doesn't work properly. So we got to put new solenoid in there. Remanufacturing solenoids, I don't think…."* (Audio file - 22:50/1:57:00)
Operating standards	ISO 9001:2008 certification (Web)
Future of Remanufacturing	*N/A*

Table 10: Analysis of interviews, field notes and email responses – Company B

Area of enquiry	Responses (Interview and field notes) – Company B
Number of employees	*"....in UK terms we are small to medium sized enterprise of about 7m turnover of about 75 employees….for remanufacturing..….."* (Audio file1-02:52/46:20)
Product types	*"….the products mix ..…about 75% transmissions and balance engines and other pieces….."* (Audio file1- 03:18/46:20)
Sales volume	*"….at the moment we are producing around 15-16 000 units/year…across the range…..in the past we did 48,000 transmissions/year with a faulty transmission….."* (Audio file1- 03:54/46:20)
Cleaning methods	*"….we have aqueous chemical washers, we have pressure washers using carborundum grits like sand, we have some individual processes which are guys working with little brushes…it cleans Aluminium."* (Audio file1- 37:37/46:20) *"…all the components put together then it has to be cleaned…we have aqueous chemical wash,……dirty parts….it will come out much cleaner like those over there…"* (Audio file2- 41:38/1:48:25) *"….we are talking about cleaning ...we have some more here, these three(3) contains small stones which are rattle,...we put gears and components in there and they just rolled around and it cleans them very very well….we have a bigger version here…you'll be able to see better….components in there with some liquid and it vibrates and lift them up to the top, tit really helps cleaning them well.... There we saw chemical agitating, spray one, this system (vibrating grits), and some of the guys just using ordinary parathane or kerosene- brushing..."* (Audio file2- 01:07:28/1:48:25) *"..that's another agitator a smaller version of what we've seen over there…the entire tray is going up and down..* (Audio file2- 01:09:58/1:48:25) *"…Parathane....it has filters in there(barrel of cleaning liquid), but when it gets too dirty, it belongs to sub-contract cleaning company, they come and take it away, leaving a cleaned one they will the clean the dirty one and it will be used again.. It's(Parathane) just one of the best media for cleaning oil and grease "*

Cleaning methods…	(Audio file2- 01:35:58/1:48:25) *"…(Engine cleaning) this is another cleaning method which is shot blasting, these blasters….you put a lot of components in there and they are rotated, and then these fans at the bottom will shot at them soft metal iron shots…when things are very clean they are very light grey colour…."* (Audio file2- 01:36:50/1:48:25) *Q: "How many trays (of gearbox components) can be put at a time to the tank washer?"* *A: "…six (6) probably…"* (Audio file2- 43:22/1:48:25) Cleaning chemicals : 70-85 ºC - 'Ardrox®' range high performance cleaners (Field notes on 13/12/2012)
Cost of cleaning	*"..Cleaning is the most expensive and the most difficult part of remanufacturing…Because it takes a lot of time, whatever the method used it takes a lot of time, If you could automate it completely, it will be a great benefit to anybody in remanufacturing…"* (Audio file2- 01:11:00/1:48:25)
Cleaning and other process times	*"…..on labour (cost) ....we will measure our processes…a typical transmission will take 3 hours(to remanufacture) from the beginning to the end -labour time, actual process time may be (spanned through) 2 days but it is 3 hours working time…"* (Audio file1- 36:25/46:20) *"..Cleaning is the most expensive and the most difficult part of remanufacturing…Because it takes a lot of time, whatever the method used it takes a lot of time, If you could automate it completely, it will be a great benefit to anybody in remanufacturing…"* (Audio file2- 01:11:00/1:48:25) *"…how long it take you ….…to put things together (Reassemble a transmission) about 40 minutes…."* (Audio file2- 01:21:06/1:48:25) *"…we probably take 20 minutes to inspect a gear box…it's not long"* (Audio file2- 51:56/46:20) *" ….some of the (cleaning) machines have cycle time….we have aqueous chemical washers, we have pressure washers using*

Cleaning and other process times…	*carborundum grits like sand, we have some individual processes which are guys working with little brushes…it cleans Aluminium."* (Audio file1- 37:37/46:20) *"…because a lot of people will reduce their cleaning and then paint the products….so you get a good visual finish but most of our customers prefer to have natural material rather than painted…"* (Audio file1- 38:40/46:20) *Q:"Is it (cleaning) the longest process?",* *A:"To get the finish of the some of the transmissions that you've seen which are very clean and which are good enough to go as new, can take 30 minutes, one man with one of the pressure guns… which is a lot of time."* *Q:"Everything for 30 mins or…?"* *A:" Just a case(Al) 30 mins and the back case another 30 mins"* *Q: "and the gears and other parts to clean with machines?"* *A: "that doesn't matter so much, because they are going into process machines 4 or 5, 6 at a time. You switch it on and walk away and do something else. When we got somebody standing there that's the problem, that's where the cost is……so we need somebody to come up with a very cheap method of cleaning, Aluminium particularly, instantly"* *Q: "Cheap and quick?"* *A: "Yeah there is a good task for you....yeah because _____ said to me that there are opportunities for you guys to do tasks as well… so you should base that challenge on cleaning finding a best way of cleaning…"* *Q: "because cleaning is the most difficult process, can we say that it is the most expensive one?"* *A: "It's probably the most expensive in labour…yes. Cleaning uses much higher % of the total process time than it really should"* (Audio file3- 01:04:33/1:48:25) *Q: "do you think cleaning time is higher than other operations for a gear box?"* *A: "It's probably at least as much as the assembly time….the cleaning probably takes as long as assembling the gear box…, it takes about 40 mins to assemble one of those big gearboxes, cleaning is similar and disassembly will be/may be 25mins ..Something like that."* *Q: "Since you are paying hourly rate then higher cost is going to cleaning?"* *A: "yeah it is pretty much the same rate for everybody,… if we can reduce the cleaning time then it affects the whole programme"*

Cleaning and other process times…	*Q: "then after cleaning then we need think whether we are creating new bottlenecks, in case if you improve the cleaning time?"* *A: "I think if we improve cleaning, which you can see the bottleneck down there today, then it will put more load into the inspection area…..then he would become a bottleneck. Then if it is a people bottleneck it is easy because we can always put people into it, if it is s machine bottleneck then it is difficult because it is process controlled"* (Audio file3- 01:08:45/1:48:25) *Q: "Other than time, do you need to spend so much on chemicals?"* *A: " Yeah, as well"* *Q: "Is it more compared to labour cost?"* *A: "It is (labour) more we usually spent, but because of the dirt and grease in them a lot of them have to do manually just to remove them because it is so thick, chemicals can't remove them. So the only way to do the process that we'll have very high pressure aqueous chemicals, but then you need a special container because it's going to go everywhere because you're talking a 1,000 psi to do some of that stuff.* *Q: "Not economical then, but there may be machines, do you design already?"* *A: "No. they are quite expensive, remanufacturing in the world we live in with the size of our company we don't have a lot of cash to invest.…..yeah….cleaning is the big problem because everything has to be cleaned doesn't matter who do it."* (Audio file3- 01:34:20/1:48:25)
Difficulties in cleaning operation	*"…because these parts are working inside the gearbox they may get very…. a lot of oil burnt onto them….so we have to use a chemical which is strong enough to remove it…..if you put Aluminium in there it will eat it…"* (Audio file2- 43:02/1:48:25) *"…it goes through this tank and then it goes through that tank, so it has two (2) tank washers….this is for different units.. I think this is probably for the cases(housings)…."* (Audio file2- 43:26/1:48:25) *"…..this is washing…..they've been blasted and then we just held here while they going through next point…so the process is dismantle in this area, wash them, spray and blast them if we need to, wash under the other bath and then put them through inspection…"* (Audio file2- 44:08/1:48:25)

Difficulties in cleaning operation…	*"….If we have cores, and if we have parts, and we've got orders, the next one which causes problem is Cleaning and it is the biggest individual process…..cleaning of dirty engines and dirty gearboxes is a difficult process"* (Audio file3- 01:04:03/1:48:25) Q: *" In general, cleaning is a problem unique to Company B or..?"* A: *"Cleaning is a problem unique to remanufacturing. Everybody that remanufactures. Those taxi engines that we talked about, the VM diesel… some of those engines take a whole day to clean… because they are so dirty* (Audio file3- 01:33:55/1:48:25)
Operating standards	*"…..for automotive remanufacturing in worldwide it is TS16949… it is the most important of the approval…."* (Audio file1- 05:15/46:20) *"…I think with the cleaning we have a standard for the results, so we know how we got to finish. The sequence they do or the tools they used are very much down to themselves…."* (Audio file2- 01:07:28/1:48:25)
Future of Remanufacturing	*Q: "What would be the future of remanufacturing?"* *A: "I think remanufacturing is going to continue, no question about it. It is going to get much more technical, the pure mechanical remanufacturing is going to reduce and requirement for electronics and mechatronics is going to be increased dramatically…we are seeing now the mechanical one, the engine and the gearboxes, that the demand is dropping, some of that is the economy at the moment, but they are generally lasting better they're performing better, they're better designs….. But electronics, because there are so many more electronic elements within cars and trucks, there is more opportunity for them to fail….hard to find where the fault is. ….that's why we are looking at the electric vehicles, the battery packs the, DCT transmissions, we need to be fully adapted to remanufacturing mechatronics and electronics. But we are not yet but soon we'll be."* *(Audio file3- 01:28:25/1:48:25)*

Table 11: Analysis of interviews, field notes and email responses – Company C

Area of enquiry	Responses (Interview and email) – Company C
Number of employees	*Q: "1.What is the number of employees employed in the reman division?"* *A:"1. There are about 300 employees in but about 6000 in the worldwide remanufacturing divisions."* (Email response on 11/01/2013)
Product types	*Q: "2. Main products types that they remanufacture (ex. diesel engines, transmission, and what else)?"* *A: "2. Products are engines (mostly diesel), transmissions, gearboxes, oil pumps, water pumps, cylinder heads, cylinder packs and individual engine components such as con-rods."* (Email response on 11/01/2013)
Sales volume	*Q: "3. On average how many units in total do they remanufacture per year?"* *A: "3. Very difficult to know but in engine terms about 100 per year (they are very large) about 4000 cylinder heads and over 20,000 components over various sorts. Transmissions are more like 30 per year. These are _______ figures"* (Email response on 11/01/2013)
Cleaning methods	*Q: "4.What cleaning processes you employee (ex. Manual cleaning, Shot blasting, abrasive cleaning, agitating in chemical baths, vibration cleaning, anything else you have)"* *A:"4. The main cleaning methods are chemical baths, shot blasting, soda blasting, vibrational cleaning and also some manual cleaning with wire brushes etc."* (Email response on 11/01/2013) "Vibration cleaning is currently used and research is going in another country for cleaning with ice crystals" (Interview notes on 08/01/2013)
Cost of cleaning	*Q: "5. In your view how much cost component is absorbed by cleaning compare to total cost of reman.?"* *A:"5. It's very hard to give you a definitive figure about cost because it is so dependent on the methods used but in term of consumables it is a large part. Probably up to 10% of the cost."* (Email response on 11/01/2013) "We got to treat cleaning and other waste using treatment plants which again involved a significant cost which other companies may choose to outsource". (Interview notes on 08/01/2013)
Cleaning and other process times	"It is very difficult to say without a proper study and it is highly complex given the number of product/part varieties to be dealt with" (Interview notes on 08/01/2013)

Difficulties in cleaning operation	"Ferrous based material cleaning is easier than Aluminium cleaning, the chemicals used to Aluminium cleaning is high cost and can cause high damage to the environment. But ferrous based alloys are easy and not that costly" (Interview notes on 08/01/2013) Q: "What is the scope of cleaning for OEM Remanufacturer verses Independent or Contract remanufacturer?" A: "The question is 'what is good enough quality?', If you sell subassemblies or parts then the requirement for cleaning is very high whereas if you are remanufacturing whole units then the requirement for cleaning is comparatively less. This is because as the customers can closely inspect and compare the remanufactured part with an original part in the market. Most of the independent remanufacturers are not into spare parts(remanufactured) selling" (Interview notes on 08/01/2013) Q: "Compared to other two types of remanufactures what difficulties does the OEM's have?" A: "We are doing large volumes of parts remanufacturing whereas independent remanufacturers do full units. When the parts manufacturing, for example if you take and C32 engine piston remanufacturing the attention to cleaning high. Why? Because customer can readily compare the reman and new one from the same supplier. So the appearance and packaging need to compete with the new one" (Interview notes on 08/01/2013)
Operating standards	ISO 9001, ISO 14001 (Interview notes on 25/07/2012)
Future of Remanufacturing	"A lot of investment is being put in to research on cleaning" (Interview notes on 08/01/2013) Q: "What are the key issues in the Remanufacturing industry?" A: " the biggest issue is the customer perception , when buying a Reman product compared to a new one. Then the varying cost of remanufacturing depending on the conditions of the core" (Interview notes on 25/07/2012)

6 RESULTS AND DISCUSSION

This chapter presents the results generated from the analysis of literature review and case studies. It discusses some claims made in the literature in the context of automotive remanufacturing. Further it summarises the companies studied. It will then discuss and answers the research questions and generate results with a summary at the end.

6.1 Comparison of end-of-use processes

The radar diagram presented in Figure 5 on end-of-use strategies by Ijomah, 2002 is presented again as Figure 49 - (a). The original diagram depicts linear or constant advancements in the three parameter axes, performance, work content and warranty. One could read the diagram, for example, the work content required for remanufacturing is as thrice as that of repair, which could be misleading. Cleaning operation is a major component of both product performance and manufacturing effort. In automotive context the cleaning efforts required during remanufacturing to bring the product/component to like new condition is far greater than the cleaning efforts required during repair or recondition. This has to be reflected in the total effort indicated in the diagram. Not only cleaning the other steps, disassembly, inspection, reassembly and testing are also required extended efforts than those required for repair or recondition. Considering those factors an analysis was carried out using the definitions of repair, recondition and remanufacture as presented in sections 1.2.1-Repair, 1.2.2-Recondition and 1.2.3-Remanufacture. Table 12 is developed based on those definitions and scored in a scale of 1 to 10 allowing sufficient range to account for minor differences existing among each strategy. A pair wise comparison was made in assigning values to each cell. Remanufacturing was given a score of 10 under each parameter as it has to be taken as the reference for comparison.

Table 12: Comparison of end-of-use strategies with comparative scores

	Repair	**Recondition**	**Remanufacturing**
Product Performance	3	7	10
Manufacturing effort	2	6	10
Warranty	1	7	10

Based on the data in Table 12 a new radar diagram is developed as shown in Figure 49 - (b). The new diagram shows more realistic and fair comparison of three end-of-life strategies. The manufacturing effort axis shows greater effort value representing the extended efforts for remanufacturing compared to repair and recondition thus indicating extended efforts for cleaning operation as well. The diagram was developed mainly considering the context of automotive remamufacturing and could be dependent on the product type or industry.

Cleaning operation helps to develop both functional and visual performances of a product. This was evident in Company B and C (Table 10, Table 11) spending greater efforts with blasting methods to get the smooth material outlook in components of gearboxes and engines. However, cleaning is given a far less attention in repair and recondition as depicted with uneven gaps in the product performance axis of Figure 49 – (b).

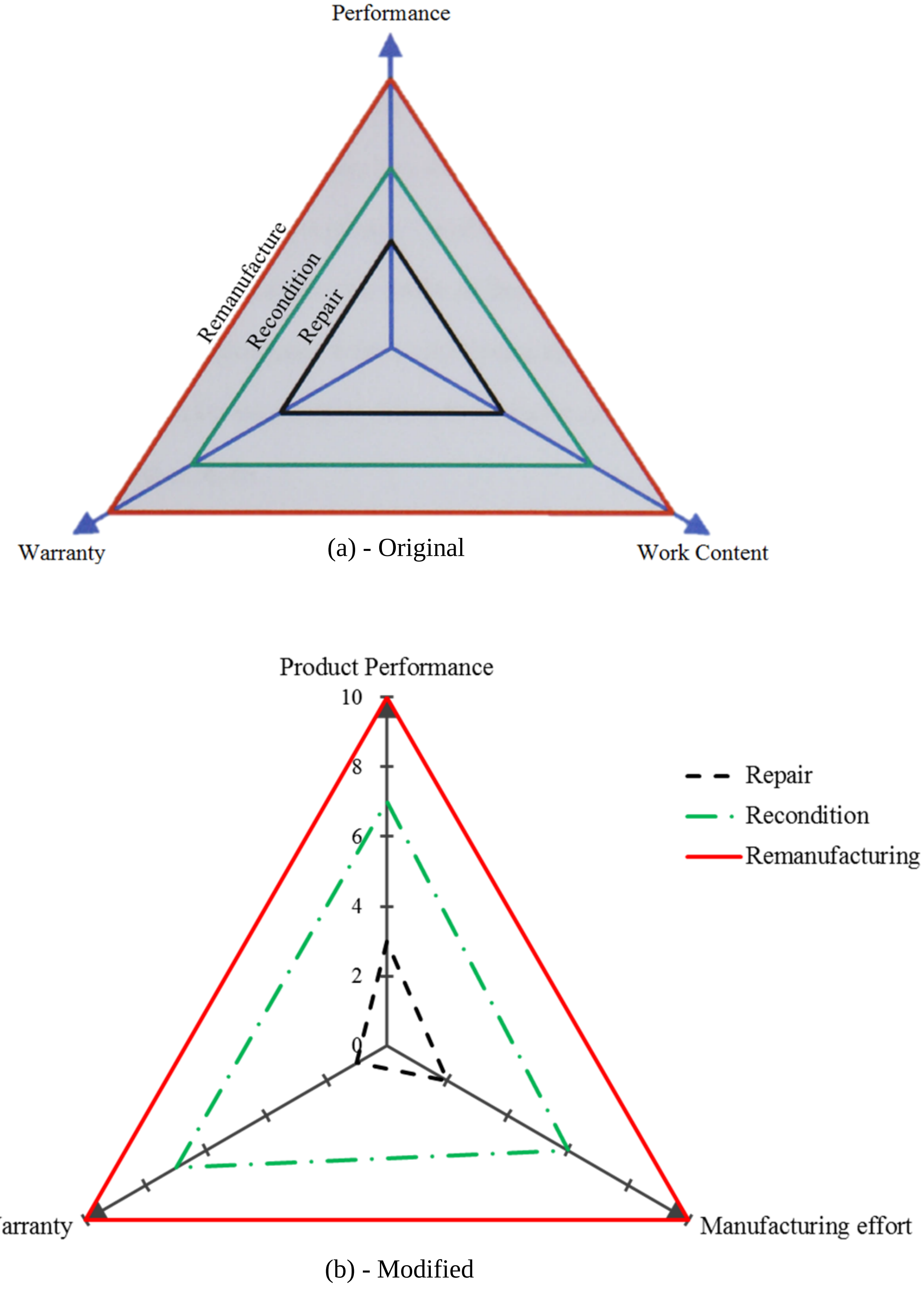


Figure 49: Comparison of repair, recondition and remanufacture [An extension to the diagram in (Ijomah, 2002) considering (British Standards Institute, 2009) and author's experience with case studies]

6.2 Comparison of companies

The process flow diagrams were developed after the detailed study during the site visits to automotive remanufacturers Company A (Figure 50) and B (Figure 51). These two are independent and contract remanufacturers respectively. Company A mainly focuses on automatic transmissions for automobiles whereas company B focuses on manual transmissions. The OEM process flow has not been developed as the study was conducted off the site. Both similarities and differences can be found in processes of A and B.

The order of process flow is the same for both companies starting with core receipt, stripping, cleaning, inspecting, reassembling, and testing. This follows the general process model for automotive remanufacturing (Figure 6). Manual cleaning and visual inspection are two processes that both companies share in common.

There are more differences than similarities in the two processes. First is the core reception process. Company B waits for a customer order to transfer cores from its own warehouse whereas Company A gets the core and the order at the same time in most of the cases. This may be due to the relatively smaller volume of operation of independent remanufacturer compared to a contract remanufacturer. Next key difference identified is the cleaning operation. Company A uses only a single spray washer followed by manual cleaning of automatic transmission parts. On the other hand company B uses variety of cleaning methods involved with machines and is putting a lot of effort on the cleaning of manual transmission parts. Inspection process is more complex in Company A, as it has to deal with torque converter and hydraulic control unit apart from the gear set. They have vacuum test and solenoid flush test to inspect the hydraulic control units. However, with manual transmissions in Company B only visual inspection with basic measuring instruments are sufficient for inspection process. The mode of material flow within work station is more streamlined and organised in Company B than Company A. Company B uses dedicated carrier trays for common models of transmission to allow an error free flow of material through conveyors utilising some of the lean manufacturing tools effectively. But in company A, the process flow is less streamlined in terms of material flow and arrangement of functional areas.

Table 13 compares the backgrounds of each company used for case studies. The first three columns represent Independent, Contract and OEM remanufacturers in the automotive sector respectively. It illustrates how cleaning operations vary from company A to C. The table is a summary of the back ground data discussed in Chapter 4: Industry case studies.

Table 13: Comparison of companies

	Company A	Company B	Company C	Company D
Sector	Automobile	Automobile	Medium to heavy duty machinery	Photocopier
Nature of business	Both automatic and manual transmission remanufacturing	Manual transmission and engine remanufacturing	Diesel engines, transmissions, drive chains, cylinder heads remanufacturing	Photo copier remanufacturing and after sales services
Category	Independent remanufacturer	Contract remanufacture	OEM	Independent remanufacturer
Company size (employees)	25 approx. SME	75 approx. SME	300 approx.	15 approx. SME
Average production (approx.)	600 units/year	15,000 units/year	Engines -100/yr Components – over 20,000/yr	400 units/year
Core sourcing	Mainly from individual clients	Received from OEM	From customers (business or individual)	From individual customers
Disassembly	Mostly manual	Mostly manual with customised machine aids	Manual and specific machine aided	Manual
Cleaning	Manual, Machine aided (spray cleaner) Uses aqueous-based detergents and degreasers	Manual, Machines (shot blasting, Spray , Submerged, Vibration glitz) Uses aqueous-based detergents and degreasers	Manual, Machines Chemical baths, shot blasting, soda blasting and vibrational cleaning	Manual Uses aqueous-based detergents
Inspection	Manual *(for gearbox and torque converter)* and Machine *(For Hydraulic control unit test: Vacuum test, Solenoid flush test)*	Manual with assistive tools *(surface gauges, magnifier glasses)*	Manual and Machine	Manual
Reassembly	Manual Machine (Electric hoists)	Manual and Machine aided *(Bearing and gear pusher, electric hoists)*	N/A	Manual
Testing	Machine: Auto & manual transmission test rig	Machine: Transmission test rig	N/A	Printing a test page

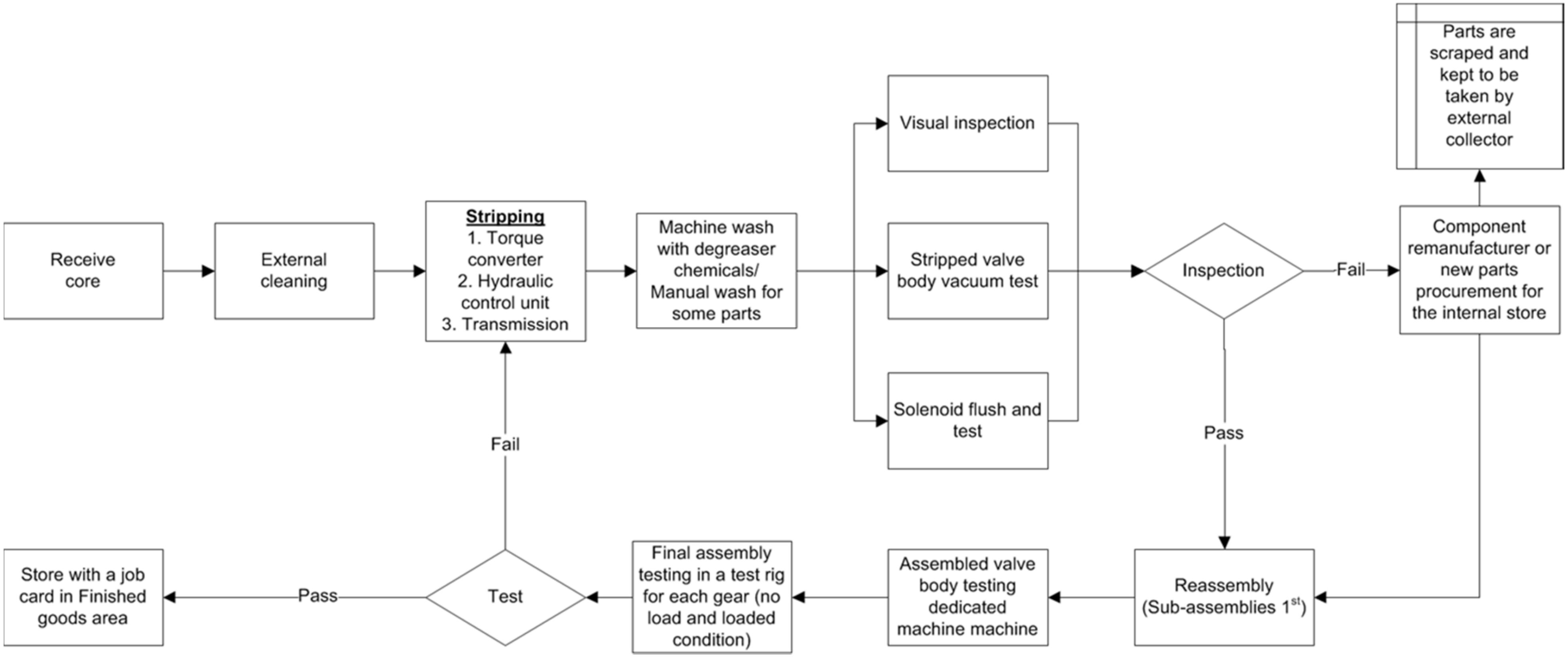


Figure 50: Process flow diagram - Company A

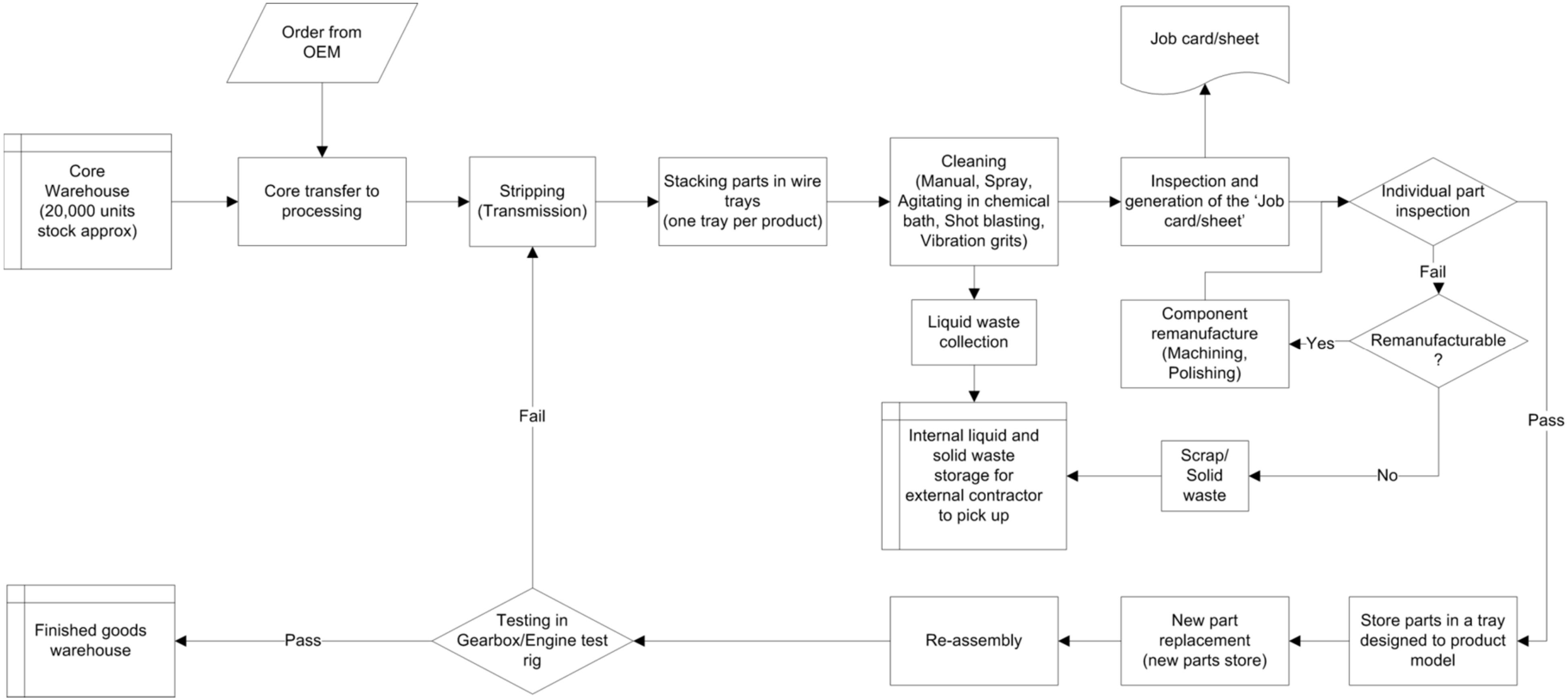


Figure 51: Process flow diagram - Company B

6.3 Research questions addressed

The knowledge gap identified from literature review on cleaning was confirmed by both companies B and C which were contract and OEM remanufacturer respectively. The discussion here will be organised in the order of addressing the research questions.

6.3.1 Why cleaning is essential in products remanufacturing?

This question was set to help investigate the technical requirements of cleaning during remanufacturing. The technical factors were studied in all three automotive remanufacturers A, B and C using responses analysis of Table 9, Table 10 and Table 11 in the Data Analysis chapter. References do Data Analysis chapter tables were mentioned in the discussion bellow. The factors identified are as follows;

- **To bring components to like new appearance –** By definition, remanufacturing requires the product to be functional and look in an as new condition. This is a main requirement of customers in the remanufactured product market. Company B (Table 10) uses various techniques to bring the parts of manual transmission to a like new appearance. In particular, both companies B and C (Table 10) use shot blasting to clean gearbox housings to bring the metal outer appearance back to the used transmission rather than painting it. The main element in automotive parts cleaning is to remove the lubricant oil and carbon deposits from metal parts. Degreaser chemicals like kerosene are being used for this purpose with a variety of machine arrangements, like spray cleaning and submerged/dipped cleaning.

- **To facilitate inspection –** Most of the time, inspection is visual for automotive parts apart from the valve body and solenoid test(Table 9) in automatic transmission. So it is essential to have clear access to the metal surface with improved observation. Cleaning helps to uncover any minor cracks and deformations of any essential features like a tooth of gear wheels. Furthermore, cleaning helps identify surface failures such as ‘Pitting’ of gears. Company A and B use visual inspection to a greater extent to assess the quality of used gear wheels during remanufacture as they are the most critical components (Table 10) of a transmission. Cleaning by vibrating grits greatly helps to identify such surface failures or impairments in critical components like gears and pistons.

- **To facilitate efficient heat transfer –** With time, there could be thick deposits of carbon or other residue on the components and internal walls of automotive transmissions and engines as mentioned by company B (Table 10). One major purpose of lubricant oil of a transmission system or engine is to carry away the generated heat during operation thus maintaining the system within the designed operating temperature.

  When the engine is considered, heat transfer is more complex and vital due to high heat generation and complexity of the cooling system. Heat generated inside the combustion chamber needs to be transferred efficiently to the coolant which runs in the wall or block of the engine. Heat generated from moving components outside the combustion chamber, such as the crank shaft and bearing-ends of connecting rods, is absorbed by the lubricant oil and subsequently transferred to the casing and then to the engine coolant. Carbon deposits and other residue (Table 10) act as barriers to heat transfer thus causing performance impairment and excessive wear. Hence, keeping the components of both engine and transmission clean is vital for effective and efficient heat transfer. This will help to attain the as new performance.

- **To achieve minimum friction during operation** - In automotive transmissions and engines, most of the parts inside are moving at very high speed, often submerged in lubricant oil. This creates considerable friction between metal and oil and also between metal-mating surfaces. A proper cleaned and polished surface, as with vibration grits cleaning by companies B and C (Table 10 and Table 11), is essential to keep the coefficient of friction down and increase the efficiency of the product. So this is another important reason for component cleaning.

6.3.2 How much effort is required for cleaning compared to overall remanufacturing effort?

None of the case companies has carried out a separate account to calculate the exact cost of cleaning. It may be due to the difficulty in absorbing overheads in a factory environment apportioned to cleaning during remanufacture as mentioned by company C (Table 11). However, during the interviews, an attempt was made to figure out an approximate cost of cleaning as a proportion of the total cost of remanufacturing. Company A takes around one hour to fully clean an automatic transmission which is about 17% of total remanufacturing time of six-seven hours of total remanufacturing time (Table 9). In company B, the cleaning operation of a manual transmission takes about 33% (Calculation based on time data in Table 10) of the total remanufacturing time during a manual transmission remanufacture, using both manual and machine processes. This is the same as the time taken for re-assembly of a transmission according to Company B(Table 10). Manual cleaning costs more than machine cleaning due to direct labour costs as opposed to machine cleaning. This is because capital costs of machines are apportioned over a longer period of time and the operating costs, like overheads and consumables, are relatively low compared to direct labour cost. The time spent on manual cleaning represents a fair enough picture of its importance within the total remanufacturing process. So the manual cleaning time together with machine cleaning is a critical factor when minimising cleaning costs.

Furthermore, the cost of cleaning consumables is higher as specific chemicals have to be bought for cleaning various types of material, including aluminium. Company C indicated that it spends around 10% (Table 11) of the total cost of remanufacturing only for consumables used for cleaning, excluding any labour or other overheads. It was observed from each case study that the efforts on cleaning are much higher in companies B and C compared to company A. This is illustrated in Figure 55 with respect to the factors which affect cleaning difficulty. It is beyond the scope of this project to establish the exact costs of cleaning for one particular product. This could be covered within a PhD research project on extensively narrowing the identified research gap. Further a quantified value would be much more appealing in attracting stakeholders in minimising cleaning costs.

6.3.3 Which factors make cleaning more difficult?

One of the main objectives of this research is to confirm and validate the factors found in literature on cleaning and to find any new factors. The factors which make cleaning more difficult are as follows.

1. **Part complexity –** This refers to the shape and size complexities of components being remanufactured as mentioned in (Hammond et al., 1998). Intricate geometries encourage tough deposits of debris and make it difficult to effectively utilise cleaning liquid or brushes. For this reason, most cast aluminium transmission housings/casings (Figure 52) are manually cleaned following a machine cleaning.

Figure 52: Intricate shapes of a transmission casing

Apart from the shape the size of parts, small orifices and gaps in valves in automatic transmissions (Figure 53) make it difficult to clean too. This demands excessive manual and machine cleaning, hence increasing the cost of cleaning.

Figure 53: Cleaning of valves in the hydraulic controller unit of an automatic transmission

This factor was identified in the literature(Hammond et al., 1998) and confirmed by all three case companies.

2. **Material type** - In automotive remanufacturing, the majority of parts are made out of steel, aluminium and other alloys. Each type of material may need different methods and chemicals during the cleaning process (Company B (Table 10) and C (Table 11)). This demands an additional step of sorting some materials for the respective cleaning processes. The best example is the aluminium housing of transmissions. The cleaning

of aluminium housings is different from steel-parts cleaning. Some chemicals used for steel component cleaning may not be used to clean aluminium. In company B, there are separate tanks for aluminium component cleaning with an operating temperature range of 70-85 ºC using 'Ardrox®' range high performance cleaners for automotive cleaning. Even with shot blasting, if the blast pressure is increased it may cause a pitted surface in the aluminium casings. Therefore, extra care is required when cleaning aluminium, which was emphasised by both company B(Table 10) and C(Table 11). Furthermore, there are also some non-metallic components involved in some products, which again need extra care. This factor was also mentioned in literature (Hammond et al., 1998) and confirmed with case studies.

3. **Compliance with environmental regulations –** There are mainly solid and liquid forms of waste during remanufacturing. Considering only the cleaning operation, the waste liquids are wash-away chemicals and degreasers. The solid waste could be residues of material used in shot-blasting, grits used in vibration cleaning, any packaging/containers of chemicals or consumables used in cleaning. Disposal of these wastes is regulated by the UK environmental agency. The waste needs to be treated before disposal in the ways specified by the regulations. Companies A and B collect their liquid and solid wastes in containers to be collected by a licenced contractor (Table 10) whom they pay for collecting and treating the waste on their behalf. However, company C is a larger volume operator and they insource the waste treatment facilities, the operating and maintenance of which is expensive. Company B and C practise the ISO 14001 environment management standard. The greater the volume of emissions and opting to treat waste in-house results in higher costs per product compared to outsourcing, as indicated by company C (Table 11). As environmental regulations become increasingly tighter, compliance puts an additional burden on remanufacturing, especially with regard to the cleaning operation.

4. **Excessive debris –** This was a factor repetitively mentioned in literature. It is obvious that the higher the debris, the higher the cleaning effort. For example, in company B the cores are stored at a large warehouse where there is a lot of dirt and dust accumulated on the cores. The cores that are received from the customers of company C have been used under tough working conditions causing each and every component to have various amounts of debris, often requiring cleaning before disassembly. This requires additional labouring and hence excessive costs of cleaning.

Compared to external debris, internal deposits of carbon require more effort to remove with cleaning. Over usage with improper maintenance, such as change of engine or transmission oil according to manufacturer's guidelines, can cause tough carbon deposits on internal components and on the internal walls of transmission/engine housings. Internal deposits are much critical to like-new performance of the product hence require greater attention on cleaning.

5. **Corrosion –** This factor has been mentioned in the literature (Hammond et al., 1998) related to automotive remanufacturing industry in general. The case studies undertaken are mainly dealing with the remanufacture of engines and transmissions. The outer casings are mainly made out of aluminium or alloys which do not get corroded. The internal parts like gear wheels, shafts and pistons operate within a lubricated environment and are made out of non-corrosive materials like, stainless steel, aluminium, brass and other alloys. So this factor is less applicable to companies A(Table 9) and B(Table 10) unless the cores are abandoned for too long. However, when remanufacturing whole units, including vehicle chassis and mounting mechanisms, corrosion will be the main factor that delays the cleaning operation, as confirmed by Company C. Therefore, corrosion was not found critical with the case companies as far as transmission and engine remanufacture is concern.

6. **Form of output in the market –** Automotive remanufacture could take place at different levels/forms of the same product. For example, there is a market for remanufactured engines and at the same time remanufactured pistons, which are small components inside the engine. In practise, the level of cleaning required for remanufacturing the whole engine and remanufacturing the pistons alone is different. In remanufactured component/spare-part sales the attention to detailed cleaning is much higher as both remanufactured and brand new components are readily available in the market for customer inspection according to case C (Table 11). A customer would not opt to make the buying decision if the remanufactured component is not visually appealing same as the new counterpart even at a lower cost. If we take a remanufactured piston versus a new piston for example, both are available with the same vendor for the customer to inspect before buying. In order to be competitive with new counterparts, higher attention to cleaning and polishing is required.

   Whereas, in the case of full-engine remanufacture this aspect is not as critical as the remanufacturer assures like-new performance of the engine with a matching warranty.

This demands excessive efforts of cleaning in component remanufacture. This may be at least few additional runs of polishing operation for a piston and likewise for other components. Therefore the form of output in the market could be a factor that affects the cleaning costs. This factor was not found in literature but revealed from a detailed discussion of company C's cleaning issues. This issue is not reflected in companies A and B as they mainly remanufacture whole units of engines and transmissions.

This should not be confused with the definition of remanufacturing, thinking that a remanufactured product should be cleaned to be the same as the new product. Remanufacturing is defined as 'returning a used product to at least its original performance with a warranty that is equivalent to or better than that of the newly manufactured product' (British Standards Institute, 2009; Ijomah, 2002). Both component and whole-product remanufacturing discussed above matches well with this definition.

7. **Cleaning methods used –** This factor was revealed with respect to the transmission casing cleaning operation. Company B and C uses shot blasting (Table 10 and Table 11) to bring the aluminium casing back to its original metal appearance after cleaning by kerosene and aqueous chemicals. However, like-new condition is achieved in company A by spray painting (Table 9) the aluminium casing, which is a quick and cost-effective method. Painting is done after a spray cleaning operation with aqueous detergents. In this respect, some cleaning methods used may affect the cost of cleaning. However, in both cases the final product matches the OEM performance standard. The approach to cleaning may be defined by the individual company's business model. Independent remanufacturers have a business model with low profit margin and highly customised service. So they need to keep their costs to a minimum, while meeting the required performance to provide a warranty equal or better the newly manufactured product.

The factors affecting effort/cost of cleaning are summarised in Table 14.

Table 14: Factors affecting high cleaning effort/cost

	Factors affecting cleaning cost	Evident by
1	Part complexity (shape and size)	Literature, Company A, B and C
2	Material type	Literature, Company A, B and C
3	Environmental regulations	Literature, Company A, B and C
4	Excessive debris	Literature, Company A, B and C
5	Corrosion	Literature, Company C
6	Form of output in the market	Company C
7	Cleaning methods used	Company B and C

The seven factors are scored against each case study company as shown in Table 15. How cleaning efforts vary for each company is scored in a 1 to 5 scale. The scoring process is based on the above discussion of seven factors affecting cleaning and is subjective to author's judgment based on the qualitative analysis.

Table 15: Scoring of cleaning efforts for each factor

Factors affecting cleaning		Score		
		A	B	C
1	Part complexity (shape, size) (Low-High)	4	3	5
2	Excessive debris (Low -High)	3	3	4
3	Material type (Easy to clean - Difficult to clean)	3	3	4
4	Corrosion (Low-High)	1	1	2
5	Compliance with environmental regulations (Outsourcing- Insourcing)	3	3	5
6	Form of output (Whole units- Part level)	2	2	5
7	Cleaning methods used (Simple - Complex)	1	5	5

The cleaning effort score is plotted against the factors of cleaning as shown in Figure 54 for ease of comparison.

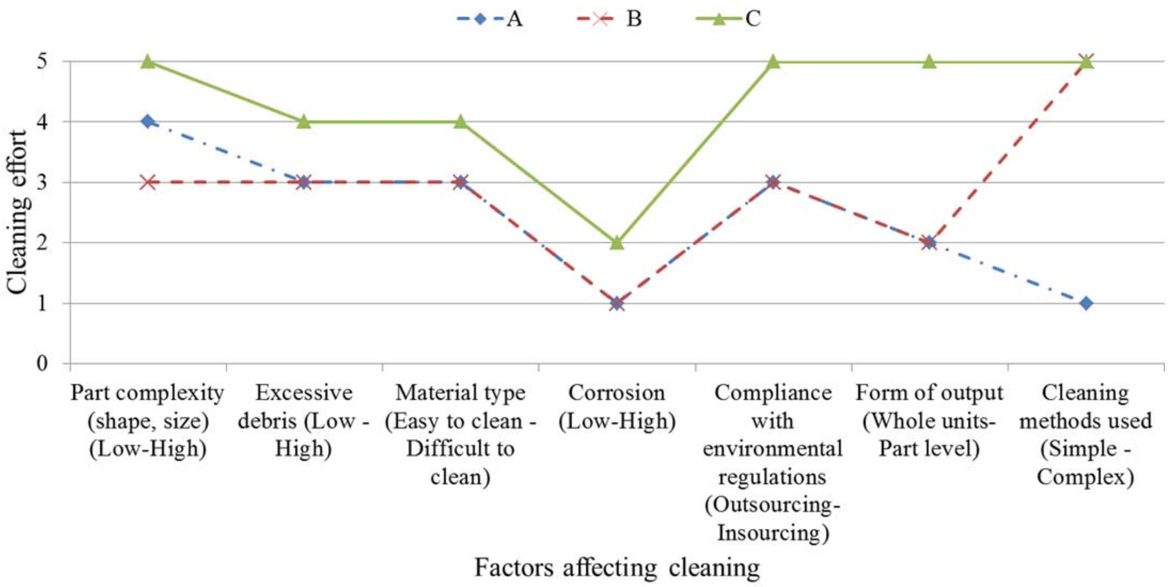
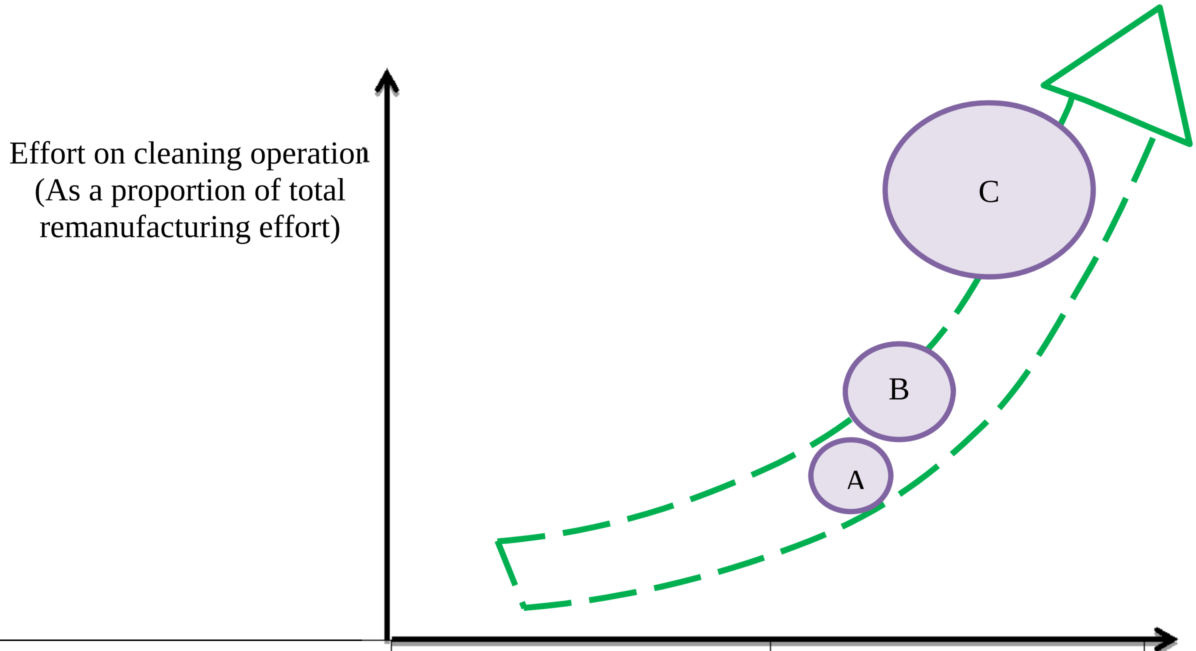


Figure 54: Cleaning efforts of each company against the factors of cleaning

The three automotive remanufacturers can be compared easily with Figure 54. It can be clearly seen that Company C is putting higher efforts for cleaning compared to Companies A and B in all areas. The part complexity is higher for Company A, as it remanufactures automatic transmissions than manual transmissions in Company B. The corrosion factor is low of all three companies as automotive transmissions and engines are normally sealed units with lubricant oil inside. Therefore the internal components have hardly any contact with external atmosphere until those are disassembled. This makes minimal corrosion of components and thus low cleaning efforts. Apart from part complexity and cleaning methods used, company A and company B shares same scores. However, the contract remanufacturer (company B) uses as much as efforts put by the OEM (company C) in terms of cleaning methods. As company C is insourcing the cleaning waste treatment, they incur higher costs to comply with environmental regulations than Companies A and B which outsource the disposal of cleaning waste.

The analysis of the three automotive companies can be depicted with respect to the cleaning effort as in Figure 55. The size of each circle denotes the relative size of the company in terms of the number of employees and volume of operation. The figure is not to a scale but represents a fair enough picture based on the qualitative information gained during the case studies and above score analysis. The x - axis represents the factors which make cleaning more costly and the y - axis represents the effort/cost of cleaning as a proportion of the total remanufacturing effort/cost in each company.



Factor		
Part complexity (shape, size)	Low	High
Excessive debris	Low	High
Material type	Easy to clean (e.g. Ferrous)	Difficult to clean (e.g. Al)
Corrosion	Low	High
Compliance with environmental regulations	Outsourcing	Insourcing
Form of output	Whole units (e.g. Complete engine)	Part level (e.g. Crank shaft, piston)
Cleaning methods used	Simple	Advanced

Figure 55 : Effort/Cost of cleaning vs. factors affecting cleaning

Figure 56 shows a snapshot of factors that cause higher cleaning costs and their sub causes. The two dimensions identified, the 'technical nature of products and processes' and 'business nature of remanufacturer' are also illustrated on the same figure encircling relevant factors.

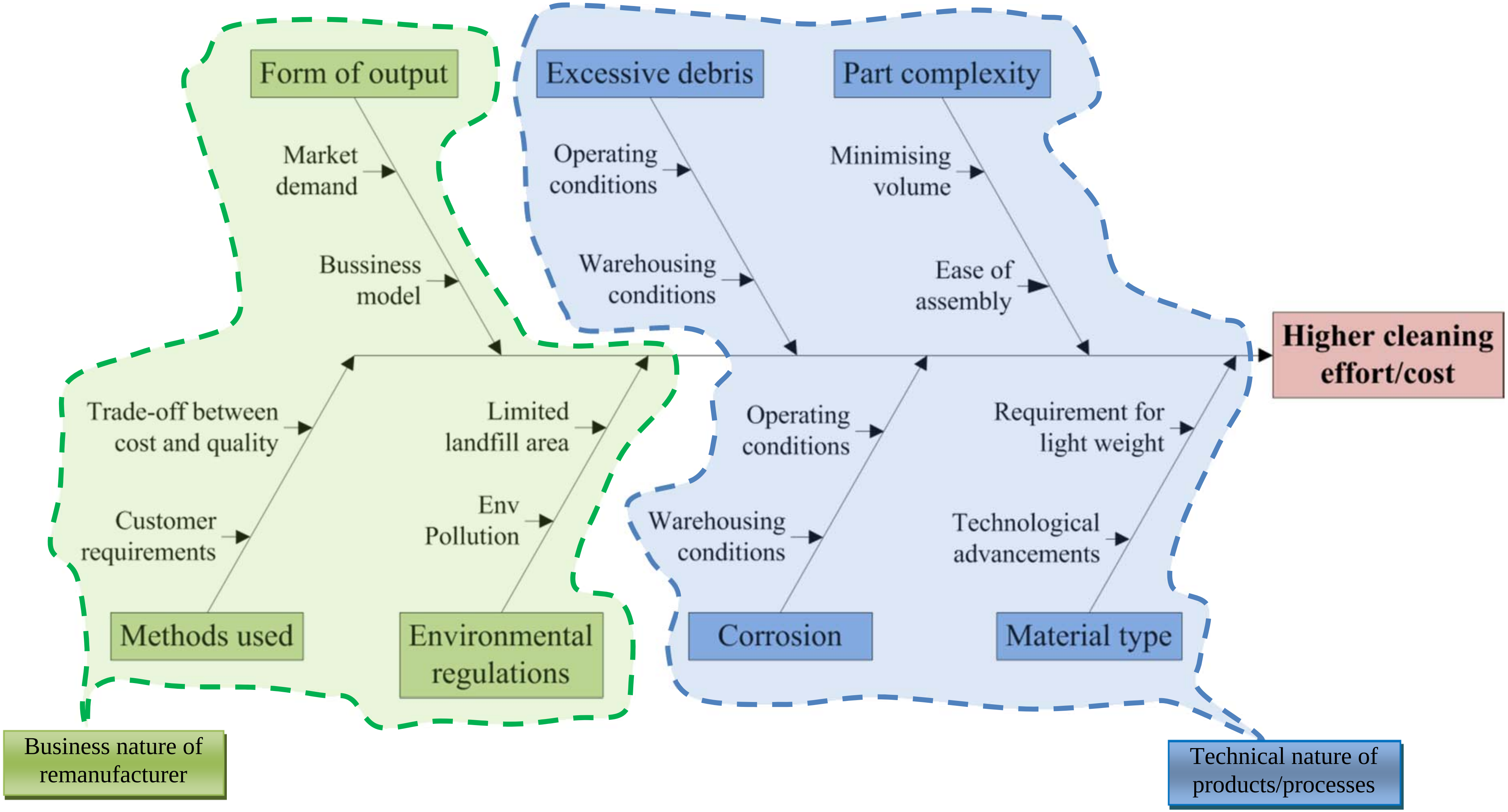


Figure 56: Factors affecting higher cleaning efforts/costs and their sub-causes

6.3.4 What knowledge could be used to make cleaning easier and more economical?

From the case studies, it was confirmed that cleaning is a critical area that contributes to overall remanufacturing effort. There was a request from company B to undertake a project to help reduce manual cleaning time which was a major cost component in terms of direct labour. The requirement of manual cleaning arises due to all or most of the factors identified above. Addressing each issue could lead to improvement in the cleaning operation.

1. **Design for Cleaning (DfC) –** Intricate geometries of components were a major obstacle making cleaning difficult. Analysis has shown that the machines used cannot reach all surfaces effectively during cleaning which, in turn, demands manual cleaning with hand tools as evident form cases A, B and C. If a transmission casing is taken as an example, the shape is so complex due to developments in manufacturing technology. During manufacture the products are designed to save material, save time and save the space occupied inside the vehicle, while keeping the required strength. Now the time has come to think about the aftermarket processes during the design stage of components. Most products are already being designed considering aftermarket processes, however it is hardly seen that they have considered the ease of disassembly and cleaning during remanufacture. Consideration of DfC during the initial design stage of the product should be highly encouraged. The focus of DfC is to re-enquire the reasons for intricate geometries of parts, selection of material, modes of intended cleaning, designed life time, environment regulations, etc. DfC could be useful not only for product remanufacture, but also for repair and recondition. So the concept of DfC could be considered as an important initiative towards sustainable manufacturing in general.

2. **Material selection –** It was identified that both metallic (steel, cast iron, aluminium, magnesium, brass, metal alloys, etc.) and non-metallic (plastic, rubber, asbestos, etc.) materials are being used in engine and transmission manufacture (Cases A, B, and C). Almost all of the non-metallic parts like oil rings, gaskets, washers, etc. are replaced during remanufacture as they may have undergone structural changes and have lost their expected properties, such as elasticity. So they do not undergo a cleaning operation. However, all metal components usually undergo a cleaning operation. The two main material types found in the case studies are steel and aluminium. The transmission casings are usually made out of aluminium however in some special

occasions with magnesium alloys. Company B (Table 10) confirmed that magnesium should be handled with care as it is prone to catch fire far more easily than aluminium or steel. Aluminium and magnesium alloys are used to make the transmission lighter, whereas earlier gearboxes are made with cast iron which is much heavier. Aluminium transmission cases are being cleaned in three ways, using a spray washer, then manually to remove tough stains and then shot blasting. Case companies have confirmed that aluminium cleaning requires expensive cleaning agents. This signals the requirement of advanced cleaning methods to clean aluminium parts much more quickly and easily than those currently used. So the selection of materials which can be handled with care during the process of cleaning would facilitate the efficient and effective cleaning for remanufacture.

3. **Products with combined materials –** If the whole component is of the same material, then it is easier to clean using an appropriate method. However, some products are made out of a combination of material types such as plastic, metal and many others bond together. An example would be the solenoids used in the hydraulic control units of automatic transmission (case A). Those are difficult to separate and the multiple material types do not permit the use of a common cleaning technique. Often these kinds of parts are replaced with new parts as the replacement costs are cheaper compared with the cost of remanufacture. It might be impossible to avoid using such material combinations as they are utilising the properties like wear resistance, electrical conductivity, heat transfer properties etc. However it is worthwhile focusing research on these areas for the design of more sustainable products in the automotive industry. Knowledge on such essential material could be used to develop effective cleaning techniques.

4. **Design to last long –** Most of the products is being designed for a single-use cycle. This is the business model practised with most products as new models are released more frequently than previously. The best examples are computers and mobile phones within the electronics industry. Also, within the automotive sector, manufacturing frequency of new vehicle models is increasing. One model/fashion will be obsolete quickly with the arrival of a new model, which is often referred to as fashion obsolescence in remanufacturing. Some manufacturers practise part proliferation with slight design modifications to discourage reuse of products in other markets as that reuse will reduce the demand for new products. These single-life products carry less durable materials to keep the cost of manufacturing to a minimum. This low durability

of material makes it difficult during the cleaning stage, which often causes breakages. Furthermore, when the designed life of components is shorter it is not worth remanufacturing them and assuring warranty in the viewpoint of remanufacturer. The emphasis here is on the requirement for the products designed to last for more than one life to facilitate cleaning and subsequent remanufacturing.

6.3.5 Research limitations

It would be better if a quantification of cost figures could be found when addressing RQ2 which would make the research of a greater impact. It is complicated as companies' cost accounting systems are not formed around each step of remanufacturing but general accounting practices like direct labour and direct material. For example the cost of complying with environmental regulations is driven by companies' general waste, sewage and remanufacturing waste from each and every step. Therefore, it is hard to find an exact figure even for cleaning materials alone. In terms of direct labour hours and machine hours spent on cleaning, these could be calculated by undertaking a proper time study of the process. However, this may require considerable amount of time and resources but would be worth doing so if the research could be extended to a PhD research project.

The process of cleaning seems to be understood at varying degrees by each remanufacturer. It appeared that the companies have their own scope of cleaning though they all were doing automotive remanufacturing. One more limitation to note is that OEMs do not specify the process of remanufacture rather expect the remanufactured product to be equal in performance to new counterparts. It is the experience and confidence of an individual remanufacturer which determines the use of processes/techniques which they believe appropriate in returning cores to like-new performance with the warranty.

As in any research, financial constraints existed in performing case studies. For example distances involved to visiting remanufacturers incurred high travelling expenses and more than one visit would have enabled more data collection. If more windows of operation were observed, with remanufacturing of different types of products/models, the results could be stronger.

6.4 Summary

The research focused on four key research questions and each was addressed during three case studies in automotive sector. From the literature review a research gap is identified as optimising cleaning during remanufacture. Why cleaning is so important, how much effort is being put towards cleaning, which factors make cleaning difficult/costly and what knowledge could be gained for product design were answered throughout this chapter. Seven factors adversely affecting cleaning efforts/cost were identified out of which five were confirmed by both literature and case studies (refer to *Table 14: Factors affecting high cleaning effort/cost* in page 102). These are part complexity, material type, environmental regulations, excessive debris, and level of corrosion (Guide Jr, 2000; Hammond et al., 1998; Sundin and Bras, 2005). The other two factors were revealed exclusively from case studies. Four measures were introduced to draw the attention of product designers and also the designers of cleaning equipment.

The factors causing higher efforts in cleaning can be broadly categorised in two different dimensions. The first dimension is the 'Technical nature of products and processes' (Figure 56). These are the difficulties which arise due to the physical characteristics of products such as shape, size and material. The technical difficulties of the cleaning processes itself can also be categorised here. These are the limitations of cleaning technology available today, such as restriction of capacities of cleaning machines, limitation of chemicals used for cleaning, etc. The second dimension is the 'business nature of the remanufacturer'. The business nature will mainly define the scope of cleaning. For example, company A opts to paint transmission cases with reduced cleaning effort to give an as new appearance, whereas company B opts to use shotblasting for the same casing to achieve the new material appearance. These two approaches involve different efforts and costs. Further the business nature will define which products are to be remanufactured and the output form of the products. This covers component level remanufacture and whole unit remanufacture. The volume of operation makes companies opt to treat cleaning waste in-house when complying with environment regulations. This also falls under the dimension of business nature. In summary, part complexities, material type, excessive debris and corrosion fall under the dimension of technical nature. Form of output in the market, method of complying with environmental regulations and methods used for cleaning falls under the dimension of business nature. Please refer to Figure 56 for a diagrammatic view of categorisation of these two dimensions.

7 CONCLUSIONS

The research was aimed to identify the significance and challenges of cleaning operation in automotive remanufacturing and thereby provide insights to reduce overall cost/effort of remanufacturing. The aim was supported with four different objectives. The first objective was to define the significance of the cleaning operation of remanufacturing. The significance of cleaning in the context of automotive remanufacturing was identified from both literature review and case studies. This was strongly evident from the case study where all three automotive remanufacturers put a lot of resources and effort into the cleaning operation. Four major reasons were found for cleaning to be essential namely, to bring components to like new appearance, to facilitate inspection, to facilitate efficient heat transfer and to achieve minimum friction during operation.

Second objective discusses the effort required for cleaning operation compared to other processes in remanufacturing. The term effort was used to represent both time and cost incurred for cleaning operation. Company A and B spend 17% and 33% of the total time respectively for cleaning operation. Further, Company C spends around 10% of total cost of remanufacturing on consumables for cleaning which is a substantial amount as that is excluding labour cost. It is difficult to take a time figure given the complexity and volume of products and parts remanufactured by company C. It can be concluded from all three case studies that the effort required for cleaning is substantial and attention is required to reducing these efforts.

The third objective was to identify factors causing the cleaning process to be more difficult and costly. This was the most widely-discussed topic throughout this research. Literature has provided very little evidence on specific factors causing high cleaning efforts/costs. Seven factors were found, of which five were from literature and were also validated with case studies. These were part complexity, material type, environmental regulations, excessive debris, and level of corrosion (Guide Jr, 2000; Hammond et al., 1998; Sundin and Bras, 2005). Two new factors were also identified from case studies which are the form of output of a product and approaches to cleaning. These factors were categorised under two dimensions. The first is the ‘Technical nature of the product and process’ which includes part complexity, excessive debris, material type and level of corrosion. The second dimension is the ‘Business nature of the remanufacturer’ which includes compliance to environmental regulations, form of output and approaches for cleaning. So it could be concluded that the third objective is well achieved with contribution to knowledge.

The fourth objective was to reveal what knowledge could be used to address the causes identified. Four main knowledge areas were revealed during case studies and literature. These are Design for Cleaning (DfC), material selection, compound material products and design to last long in the context of automotive remanufacturing. The feedback from these areas is expected to address the identified causes, hence reducing the effort/cost of the cleaning process thus reducing the total cost/effort of remanufacturing.

In conclusion, all four objectives of the research have been addressed through the research with three automotive remanufacturers. The identified knowledge areas could well be used to reduce the effort on cleaning and thus reducing the total cost/effort of remanufacturing in the long term. Hence it could be concluded that the aim of research has been achieved.

The future of automotive component remanufacture is also expected to face several issues as identified by case studies. One major issue is the increase or very high integration of electronic components in automobiles, such as sensors and controller processors. These electronic components are impossible or very hard to reuse and could easily be damaged during remanufacture. Remanufacturers are already experiencing difficulties as the costs of these components are high. The next common issue is the lack of concern on design for remanufacture and designed for cleaning. As per the case studies, it was confirmed that none of the products they deal with are designed for remanufacture.

7.1 Contribution to knowledge

Higher efforts/costs spent on cleaning during remanufacture was identified as an under-researched area from the literature and confirmed with the case studies. Research focused on four research objectives and answers four research questions. The research questions were set to find, the importance of cleaning, the effort on cleaning, the factors which make cleaning more difficult and the knowledge that can be used to improve cleaning. Seven key factors causing higher cleaning efforts/costs were uncovered through the research. These are, part complexity in terms of shape and size, type of material used, environmental regulation on waste disposal, excessive debris, corrosion, form of output in the market and approaches used for cleaning. Two main dimensions influencing the cost of cleaning were identified as the 'Technical nature of products and processes' and the 'Business nature of the remanufacturer'. The seven causes were categorised under above two dimensions (Figure 56).

The research aimed to identify the significance and challenges of cleaning operation in automotive remanufacturing and thereby provide insights to reduce overall cost/effort of remanufacturing industry. Four main knowledge areas were identified to reduce cleaning efforts and costs. Design for cleaning (DfC), material selection, use of compound material products and design for last long have been proposed in achieving the aims and objectives.

Design for remanufacture (DfRem) is a popular topic discussed in the field of remanufacturing. DfRem considers about ease of disassembly, ease of reassembly, durability of components, etc. However, what feedback is given for DfRem process from the cleaning operation is unclear. The four knowledge areas developed are expected to fill the gap in the product design phase. Furthermore, DfC not only facilitates remanufacturing but also facilitates recondition and repair. Additionally, those knowledge areas are expected to contribute towards the design of cleaning machines and related equipment (such as shotblasters, liquid agitators, spray cleaners, vibration-cleaning machines, etc.) and consumables (powder for shotblasting, granules for ball mills, chemicals used for degreasing, etc.).

A paper titled ‘What Makes Cleaning a Costly Operation in Remanufacturing? (Gamage et al., 2013)’ was published in the 11th Global Conference on Sustainable Manufacturing held in Berlin, Germany on 23rd – 25th September, 2013. The paper presents a summary of knowledge contribution through this research. A copy of the paper is attached in the appendix II.

7.2 Beneficiaries

Most of the stakeholders of remanufacturing and associated businesses would be beneficiaries of this research. These could be mainly categorised as the research community and industrial stakeholders. The immediate beneficiaries would be the researchers and academia who are in the field of remanufacturing research. They will benefit from the new research avenues opened up as the knowledge-front is expanded with this research. The research draws attention to minimising the cost of remanufacturing by improving the cleaning operation. This will support the sustainability model of the product manufacture, allowing the remanufactured product to be competitive in the market. Furthermore, competitive market demand will encourage more remanufacturing at independent and contract levels apart from OEMs. Hence the main beneficiaries would be the remanufacturers of automotive parts and components. Other industrial beneficiaries could be product designers, process designers, cleaning equipment manufacturers and cleaning consumables producers, etc. Current cleaning equipment is designed to clean products which were not originally designed for cleaning. However, once the products are designed for cleaning it would be easier to automate the full cleaning operation and cleaning equipment manufacturers may see a step change in their technology.

Finally, society at large will benefit with the cost savings transferred to the remanufactured products which are greener than before. This will help to expand the current market for remanufactured products with a huge gain in environmental savings.

7.3 Further research

The research was originally started targeting a three-year PhD and has shown satisfactory progress to proceed to a PhD during the 1st year review. Therefore, the author believes that this MPhil work has laid a good foundation for a PhD research project. A clearly under-researched area has been uncovered from literature and through case studies. The cost of cleaning is considerably higher even though the process is not that complex when compared with the complexity of products that is being dealt with. This issue is well confirmed during case studies, with company B having made a request to undertake a process improvement project for cleaning operation. Therefore, improvement of the cleaning operation would be a key concern in the remanufacturing industry. Furthermore, the literature review undertaken here clearly suggests that hardly any research has been done in the UK related to cleaning in automotive parts remanufacturing.

Design for remanufacture is a popular topic under research and designers' focus is mainly drawn to disassembly and re-assembly issues. However, the aspect of design for cleaning (DfC) is hardly discussed. It is worth quantifying the costs of cleaning to find out how significant the issue is with several case companies in the automotive sector. Then the parts or components could be prioritised depending on the difficulty of cleaning encountered with the available cleaning technology. Some more specific aspects could be identified which make cleaning difficult with regard to innovative design alterations in automotive components. Likewise, the research questions could be looked into with more depth and quality knowledge could be produced in improving overall process of remanufacture.

Another potential research area found in literature is the requirement of assessing the environmental impact of products with repetitive life cycles with remanufacture. It was revealed from the research undertaken outside the UK. However, this gap was not reflected during case studies as three out of four case companies were outsourcing the disposal of waste. This will expand the research boundary beyond the remanufacturer to the waste treatment provider thus making the impact assessment difficult. Nevertheless, if one can source all the case studies with large scale remanufacturers who in-source their waste treatment, then the impact assessment would be more feasible. A detailed discussion of this is mentioned in the later part of the literature review section.

BIBLIOGRAPHY

Amaya, J., Zwolinski, P., Brissaud, D., 2010. Environmental benefits of parts remanufacturing: the truck injector case, in: 17th CIRP International Conference on Life Cycle Engineering Proceedings. Hefei, ANHUI, Chine, p. N/A.

Ates, A., 2008. Strategy Process in Manufacturing SMEs. University of Strathclyde.

Baines, T.S., Braganza, A., Kingston, J., 2007. State-of-the-art in product-service systems. Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 221, 1543–1552. doi:10.1243/09544054JEM858

Biswas, W., Rosano, M., 2011. A life cycle greenhouse gas assessment of remanufactured refrigeration and air conditioning compressors. Int. J. Sustain. Manuf. 2, 222–236.

Boehm, M., Thomas, O., 2013. Looking beyond the rim of one's teacup: a multidisciplinary literature review of Product-Service Systems in Information Systems, Business Management, and Engineering & Design. J. Clean. Prod. doi:10.1016/j.jclepro.2013.01.019

British Standards Institute, 2009. BS 8887-2:2009. Design for manufacture, assembly, disassembly and end-of-life processing (MADE) Part 2: Terms and definitions, UK, BSI.

Chiodo, J.D., Ijomah, W.L., 2012. Use of active disassembly technology to improve remanufacturing productivity: automotive application. Int. J. Comput. Integr. Manuf. 1–11. doi:10.1080/0951192X.2012.667151

Creswell, J.W., 2002. Research Design: Qualitative, Quantitative, and Mixed Methods Approaches, Second Edition edition. ed. SAGE Publications, Inc.

Cunha, V.P., Balkaya, I., Palacios, J., Rozenfeld, H., Seliger, G., 2011. Development of Technology Roadmap for Remanufacturing Oriented Production Equipment, in: Seliger, G., Khraisheh, M.M.K., Jawahir, I.S. (Eds.), Advances in Sustainable Manufacturing. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 203–208.

DIRECTIVE 2000/53/EC on end-of life vehicles, 2000.

DIRECTIVE 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment, 2011.

Directive 2012/19/EU on waste electrical and electronic equipment (WEEE), 2012.

Dooley, L.M., 2002. Case study research and theory building. Adv. Dev. Hum. Resour. 4, 335–354.

Du, Y., Cao, H., Liu, F., Li, C., Chen, X., 2012. An integrated method for evaluating the remanufacturability of used machine tool. J. Clean. Prod. 20, 82–91. doi:10.1016/j.jclepro.2011.08.016

Easterby-Smith, M., Thorpe, R., Jackson, P., Lowe, A., 2008. Management Research. SAGE.

Eisenhardt, K.M., 1989. Building Theories from Case Study Research. Acad. Manage. Rev. 14, 532–550. doi:10.2307/258557

El korchi, A., Millet, D., 2011. Designing a sustainable reverse logistics channel: the 18 generic structures framework. J. Clean. Prod. 19, 588–597. doi:10.1016/j.jclepro.2010.11.013

End-of-life vehicles [WWW Document], 2013. . Eur. Summ. EU Legis. URL http://europa.eu/legislation_summaries/environment/waste_management/l21225_en.htm (accessed 3.7.13).

Ferrer, G., Whybark, C.D., 2000. From garbage to goods: Successful remanufacturing systems and skills. Bus. Horiz. 43, 55–64. doi:10.1016/S0007-6813(00)80023-3

Gamage, J.R., Ijomah, W.L., Windmill, J., 2013. What Makes Cleaning a Costly Operation in Remanufacturing?, in: Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions. Presented at the 11th Global Conference on Sustainable Manufacturing, Universitätsverlag der TU Berlin, Berlin, Germany, pp. 222–226.

Gehin, A., Zwolinski, P., Brissaud, D., 2009. Integrated design of product lifecycles—The fridge case study. CIRP J. Manuf. Sci. Technol. 1, 214–220. doi:10.1016/j.cirpj.2009.05.002

Georgiadis, P., Vlachos, D., 2004. The effect of environmental parameters on product recovery. Eur. J. Oper. Res. 157, 449–464. doi:10.1016/S0377-2217(03)00203-0

Giutini, R., Gaudette, K., 2003. Remanufacturing: The next great opportunity for boosting US productivity. Bus. Horiz. 46, 41–48. doi:10.1016/S0007-6813(03)00087-9

Gobbi, C., 2011. Designing the reverse supply chain: the impact of the product residual value. Int. J. Phys. Distrib. Logist. Manag. 41, 768–796. doi:10.1108/09600031111166429

Gottberg, A., Morris, J., Pollard, S., Mark-Herbert, C., Cook, M., 2006. Producer responsibility, waste minimisation and the WEEE Directive: Case studies in eco-design from the European lighting sector. Sci. Total Environ. 359, 38–56. doi:10.1016/j.scitotenv.2005.07.001

Guide Jr, V.D.R., 2000. Production planning and control for remanufacturing: industry practice and research needs. J. Oper. Manag. 18, 467–483.

Guide Jr, V.D.R., Li, J., 2010. The Potential for Cannibalization of New Products Sales by Remanufactured Products*. Decis. Sci. 41, 547–572.

Guide Jr, V.D.R., Van Wassenhove, L.N., 2009. The Evolution of Closed-Loop Supply Chain Research. Oper. Res. 57, 10–18. doi:10.1287/opre.1080.0628

Hammond, R., Amezquita, T., Bras, B., 1998. Issues in the automotive parts remanufacturing industry: a discussion of results from surveys performed among remanufacturers. Eng. Des. Autom. 4, 27–46.

Hatcher, G.D., 2013. Integrating Design for Remanufacture into the Design Process —the Operational Factors (PhD Thesis). University of Strathclyde, UK.

Ijomah, W., 2010. The application of remanufacturing in sustainable manufacture. Proc. ICE - Waste Resour. Manag. 163, 157–163. doi:10.1680/warm.2010.163.4.157

Ijomah, W.L., 2002. A Model-based Definition of the Generic Remanufacturing Business Process (PhD Thesis). University of Plymouth, Plymouth, United Kingdom.

Ijomah, W.L., Chiodo, J.D., 2010. Application of active disassembly to extend profitable remanufacturing in small electrical and electronic products. Int. J. Sustain. Eng. 3, 246–257. doi:10.1080/19397038.2010.511298

Ijomah, W.L., Hammond, G.P., Childe, S.J., McMahon, C.A., 2005. A robust description and tool for remanufacturing: a resource and energy recovery strategy, in: Environmentally Conscious Design and Inverse Manufacturing, 2005. Eco Design 2005. Fourth International Symposium on. pp. 472–479.

Ijomah, W.L., McMahon, C.A., Hammond, G.P., Newman, S.T., 2007. Development of design for remanufacturing guidelines to support sustainable manufacturing. Robot. Comput.-Integr. Manuf. 23, 712–719.

Ilgin, M.A., Gupta, S.M., 2010. Environmentally conscious manufacturing and product recovery (ECMPRO): A review of the state of the art. J. Environ. Manage. 91, 563–591. doi:10.1016/j.jenvman.2009.09.037

Inderfurth, K., 2005. Impact of uncertainties on recovery behavior in a remanufacturing environment: A numerical analysis. Int. J. Phys. Distrib. Logist. Manag. 35, 318–336. doi:10.1108/09600030510607328

Jayaraman, V., Jr., V.D.R.G., Srivastava, R., 1999. A Closed-Loop Logistics Model for Remanufacturing. J. Oper. Res. Soc. 50, 497–508. doi:10.2307/3009998

Kapetanopoulou, P., Tagaras, G., 2011. Drivers and obstacles of product recovery activities in the Greek industry. Int. J. Oper. Prod. Manag. 31, 148–166. doi:10.1108/01443571111104746

Kerr, W., Ryan, C., 2001. Eco-efficiency gains from remanufacturing: A case study of photocopier remanufacturing at Fuji Xerox Australia. J. Clean. Prod. 9, 75–81. doi:10.1016/S0959-6526(00)00032-9

King, A.M., Burgess, S.C., 2005. The Development of a Remanufacturing Platform Design: A Strategic Response to the Directive on Waste Electrical and Electronic Equipment. Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 219, 623–631. doi:10.1243/095440505X32526

King, A., Miemczyk, J., Bufton, D., 2006. Photocopier remanufacturing at Xerox UK A description of the process and consideration of future policy issues, in: Brissaud, D., Tichkiewitch, S., Zwolinski, P. (Eds.), Innovation in Life Cycle Engineering and Sustainable Development. Springer Netherlands, pp. 173–186.

Krikke, H., 2010. Opportunistic versus life-cycle-oriented decision making in multi-loop recovery: an eco-eco study on disposed vehicles. Int. J. Life Cycle Assess. 15, 757–768. doi:10.1007/s11367-010-0217-y

Kumar, S., Putnam, V., 2008. Cradle to cradle: Reverse logistics strategies and opportunities across three industry sectors. Int. J. Prod. Econ. 115, 305–315. doi:10.1016/j.ijpe.2007.11.015

Lund, R.T., 1983. Remanufacturing, United States experience and implications for developing nations. Center for Policy Alternatives, Massachusetts Institute of Technology.

Meredith, J., 1998. Building operations management theory through case and field research. J. Oper. Manag. 16, 441–454.

Michelsen, O., 2007. Eco-efficiency in redesigned extended supply chains; furniture as an example, in: Huppes, G., Ishikawa, M., Tukker, A. (Eds.), Quantified Eco-Efficiency, Eco-Efficiency in Industry and Science. Springer Netherlands, pp. 163–179.

Mollenkopf, D.A., Frankel, R., Russo, I., 2011. Creating value through returns management: Exploring the marketing–operations interface. J. Oper. Manag. 29, 391–403.

Nasr, N., Hilton, B., German, R., 2011. A Framework for Sustainable Production and a Strategic Approach to a Key Enabler: Remanufacturing, in: Seliger, G., Khraisheh, M.M.K., Jawahir, I.S. (Eds.), Advances in Sustainable Manufacturing. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 191–196.

Nasr, N., Hughson, C., Varel, E., Bauer, R., 1998. State-of-the-art assessment of remanufacturing technology. Draft Doc. Rochester Inst. Technol.

Na, W.-J., Park, H.-K., 2012. A study on remanufacturing of deactivated commercial DPF using diesel engine dynamo system in ND-13 mode. J. Ind. Eng. Chem. 18, 1377–1383. doi:10.1016/j.jiec.2012.01.035

Nnorom, I.C., Osibanjo, O., 2008. Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries. Resour. Conserv. Recycl. 52, 843–858. doi:10.1016/j.resconrec.2008.01.004

OECD, 2004. Economic Aspects of Extended Producer Responsibility. Organisation for Economic Co-operation and Development, Paris.

Okumura, S., Morikuni, T., Okino, N., 2003. Environmental effects of physical life span of a reusable unit following functional and physical failures in a remanufacturing system. Int. J. Prod. Res. 41, 3667–3687. doi:10.1080/0020754031000120104

Östlin, J., Sundin, E., Björkman, M., 2009. Product life-cycle implications for remanufacturing strategies. J. Clean. Prod. 17, 999–1009. doi:10.1016/j.jclepro.2009.02.021

Pialot, O., Millet, D., Tchertchian, N., 2012. How to explore scenarios of multiple upgrade cycles for sustainable product innovation: the “Upgrade Cycle Explorer” tool. J. Clean. Prod. 22, 19–31. doi:10.1016/j.jclepro.2011.10.001

Quigley, J., 2012. Research Methodology. Presented at the BF992 Research Methodology Course, Busineess School,University of Strathclyde, Glasgow, UK.

Ridley, S.J., 2012. Remanufacturing – Industrial Cost Models. Presented at the DM943 Sustainable Product Design and Manufacturing, University of Strathclyde, Glasgow, UK.

Sakao, T., 2007. A QFD-centred design methodology for environmentally conscious product design. Int. J. Prod. Res. 45, 4143–4162. doi:10.1080/00207540701450179

Seitz, M.A., 2007. A critical assessment of motives for product recovery: the case of engine remanufacturing. J. Clean. Prod. 15, 1147–1157. doi:10.1016/j.jclepro.2006.05.029

Seliger, G., Skerlos, S.J., Basdere, B., Zettl, M., 2003. Design of a Modular Housing Platform to accommodate the remanufacturing of multiple cellular telephone models, in: Environmentally Conscious Design and Inverse Manufacturing, 2003. EcoDesign ’03. 2003 3rd International Symposium on. pp. 243 –250. doi:10.1109/ECODIM.2003.1322670

Srivastava, S.K., 2007. Green supply-chain management: A state-of-the-art literature review. Int. J. Manag. Rev. 9, 53–80. doi:10.1111/j.1468-2370.2007.00202.x

Srivastava, S.K., 2008. Network design for reverse logistics. Omega 36, 535–548.

Stahel, W., 1994. The utilization-focused service economy: Resource efficiency and product-life extension, in: The Greening of Industrial Ecosystems. National Academies Press, pp. 178–190.

Subramoniam, R., Huisingh, D., Chinnam, R.B., 2010. Aftermarket remanufacturing strategic planning decision-making framework: theory & practice. J. Clean. Prod. 18, 1575–1586.

Sundin, E., Bras, B., 2005. Making functional sales environmentally and economically beneficial through product remanufacturing. J. Clean. Prod. 13, 913–925. doi:10.1016/j.jclepro.2004.04.006

Sundin, E., Elo, K., Lee, H.M., 2012. Design for automatic end-of-life processes. Assem. Autom. 32, 389–398. doi:10.1108/01445151211262447

Sundin, E., Lee, H.M., 2012. In what way is remanufacturing good for the environment?, in: Matsumoto, M., Umeda, Y., Masui, K., Fukushige, S. (Eds.), Design for Innovative Value Towards a Sustainable Society. Springer Netherlands, Dordrecht, pp. 552–557.

Sundin, E., Lindahl, M., Ijomah, W., 2009. Product design for product/service systems: Design experiences from Swedish industry. J. Manuf. Technol. Manag. 20, 723–753. doi:10.1108/17410380910961073

Sutherland, J.W., Adler, D.P., Haapala, K.R., Kumar, V., 2008. A comparison of manufacturing and remanufacturing energy intensities with application to diesel engine production. CIRP Ann. - Manuf. Technol. 57, 5–8. doi:10.1016/j.cirp.2008.03.004

The World Commission on Environment and Development, 1989. Our Common Future. Oxford University Press.

Tsiliyannis, C.A., 2011. End-of-life flows of multiple cycle consumer products. Waste Manag. 31, 2302–2318. doi:10.1016/j.wasman.2011.06.003

Umeda, Y., 2001. Toward a life cycle design guideline for inverse manufacturing, in: Proceedings EcoDesign 2001: Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing, 2001. Presented at the Proceedings EcoDesign 2001: Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing, 2001, pp. 143 –148. doi:10.1109/.2001.992335

Umeda, Y., Daimon, T., Kondoh, S., 2007. Life Cycle Option Selection Based on the Difference of Value and Physical Lifetimes for Life Cycle Design. Guidel. Decis. Support Method Adapt. NPD Process.

U.S. Department of Commerce, 2013. How does Commerce define Sustainable Manufacturing? [WWW Document]. Sustain. Manuf. Initiat. URL http://www.trade.gov/competitiveness/sustainablemanufacturing/ (accessed 1.15.13).

Webster, S., Mitra, S., 2007. Competitive strategy in remanufacturing and the impact of take-back laws. J. Oper. Manag. 25, 1123–1140. doi:10.1016/j.jom.2007.01.014

www.bluereachautomation.com [WWW Document], 2013. . | BlueReach. URL http://www.bluereachautomation.com/main-2/0029crop_581x400/ (accessed 3.22.13).

www.edenproject.com [WWW Document], 2013. . Sustain. Living. URL http://www.edenproject.com/

Yin, R.K., 1981. The Case Study as a Serious Research Strategy. Sci. Commun. 3, 97–114. doi:10.1177/107554708100300106

Yin, R.K., 2003. Case Study Research, Design and Methods. Sage, London,UK.

Zwolinski, P., Brissaud, D., 2008. Remanufacturing strategies to support product design and redesign. J. Eng. Des. 19, 321–335. doi:10.1080/09544820701435799

APPENDICES

APPENDIX I: Analysis of methodologies adopted by previous researchers

Table 16: Analysis of methodologies adopted by previous researchers

	Research Publication	**Purpose/Aim/Objectives of the study**	**Methodology and/or Techniques used**
1	Eco-efficiency in redesigned extended supply chains; furniture as an example (Michelsen, 2007)	To show how the eco-efficiency concept can be used to evaluate value and environmental performance	Case study (Single) Six scenarios were developed to improve extended supply chain performance SimaPro was used for standardising with respect to normalising and weighting
2	Product design for product/service systems: Design experiences from Swedish industry (Sundin et al., 2009)	To elucidate how Swedish industry has adapted their products for product/service systems (PSS)	Case study (3 Companies) Interviews product analyses in laboratorial environment
3	A robust description and tool for remanufacturing: a resource and energy recovery strategy (Ijomah et al., 2005)	Address the issue of less awareness of the definition of Remanufacturing	3 Phase research approach as in '*Eisenhardt's case study Methodology*' Literature search observational case studies (11 companies) Generic model development and validation IDEF0 – Modelling
4	Creating value through returns management: Exploring the marketing–operations interface (Mollenkopf et al., 2011)	To explore the phenomenon of returns management across a multi-disciplinary, managerial spectrum addressing the limited understanding of research topic.	Case study Interviews 2 subsidiaries
5	Aftermarket remanufacturing strategic planning decision-making framework: theory & practice (Subramoniam et al., 2010)	To developing a framework for decision making for aftermarket remanufacturing	Literature review Case studies Industry survey (18 companies)
6	Designing the reverse supply chain: the impact of the product residual value (Gobbi, 2011)	To explore the impact of the product residual value (PRV) and the loss of value over time of returned products	Case study

7	Environmental benefits of parts remanufacturing: the truck injector case (Amaya et al., 2010)	Developing a model to support the business model and to reorient the activity from cradle-to- grave to cradle-to-cradle while testing different final disposition scenarios	Case study Software used, SimaPro, CLOEE (Closed Loop Environmental Evaluations)
8	Product life-cycle implications for remanufacturing strategies (Östlin et al., 2009)	Providing decision support for different supply and demand situations (life cycle perspective)	Case study (multiple cases with multiple products) Semi-structured interviews Direct observations Documents
9	Producer responsibility, waste minimisation and the WEEE Directive: Case studies in eco-design from the European lighting sector (Gottberg et al., 2006)	To address the gaps in knowledge in relation to the influence of financial incentive to reduce waste at source through eco-design.	Literature review(to develop an analytical frame work) Case studies (8) to application in lighting sector Exploratory study
10	The effect of environmental parameters on product recovery (Georgiadis and Vlachos, 2004)	To examine the impact of environmental issues on long-term behaviour of a single product supply chain with product recovery	Dynamic simulation model based on the principles of the System dynamics (SD) dynamic model provides an experimental simulation tool, Numerical analysis
11	A Closed-Loop Logistics Model for Remanufacturing (Jayaraman et al., 1999)	To simultaneously solve the location of remanufacturing/ distribution facilities, the trans-shipment, production, and stocking of the optimal quantities of remanufactured products and cores	Mathematical modelling 0-1 mixed integer programming model
12	Opportunistic versus life-cycle-oriented decision making in multi-loop recovery: an eco-eco study on disposed vehicles (Krikke, 2010)	Studies decision making in recovery, comparing opportunistic decision making with short-term profit maximization (usually leading to one loop) versus a life-cycle perspective (leading to multiple loops).	Mathematical modelling a non-linear optimization model (NPV, ENV, recovery rate)
13	End-of-life flows of multiple cycle consumer products (Tsiliyannis, 2011)	Providing explicit expressions for the end-of-life flows (EOL) of single and multiple cycle products (MCPs)	Mathematical Model 10 step procedure with deterministic and stochastic models for EOL exit
14	Network design for reverse logistics	To provide an integrated holistic conceptual framework that	Literature review and conceptual model

	(Srivastava, 2008)	combines descriptive modelling with optimization techniques at the methodological level	development Mathematical model (Hierarchical process model for optimisation)
15	Competitive strategy in remanufacturing and the impact of take-back laws (Webster and Mitra, 2007)	To examine the impact of take-back laws within a manufacturer/remanufacturer competitive framework	Mathematical Modelling to generate two-period models
16	Impact of uncertainties on recovery behaviour in a remanufacturing environment: A numerical analysis (Inderfurth, 2005)	How cost-efficient decision making affects the product recovery behaviour.	Numerical analysis
17	The Potential for Cannibalization of New Products Sales by Remanufactured Products(Guide Jr and Li, 2010)	To address the cannibalization issue by using auctions to determine consumers' willingness to pay (WTP) for both new and remanufactured products.	Survey based Auction in 'eBay' 3 Hypotheses
18	Drivers and obstacles of product recovery activities in the Greek industry (Kapetanopoulou and Tagaras, 2011)	To find the extent of involvement of original equipment manufacturers in product recovery activities (PRA), the direct profitability of PRA and the most important specific drivers and barriers to the implementation of PRA	Survey (Questionnaire-based) Statistical analysis
19	Green supply-chain management: A state-of-the-art literature review (Srivastava, 2007)	To provide succinct classification to help academicians, researchers and practitioners to understand integrated GrSCM from a wider perspective with a classification of methodology and approach adopted.	Literature review Defining unit of analysis Classification context Material evaluation Collecting publications and delimiting the field
20	The returns management process in supply chain strategy (Mollenkopf et al., 2011)	To consider theory development related to returns management within supply chain strategy. The marketing/logistics relationship is investigated.	Grounded theory Managers in five Italian firms, across marketing and logistics roles, at strategic and operational levels were interviewed

APPENDIX II: Paper published in the 11th Global Conference on Sustainable Manufacturing, Berlin-Germany, September 2013

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7.1 What Makes Cleaning a Costly Operation in Remanufacturing?

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Abstract

Product remanufacturing is a widely accepted product reuse strategy in most industries due to its unique advantage of retaining a greater portion of added value in the initial manufacturing stage. Remanufacturing involves a sequence of operations including disassembly, cleaning, inspection, parts replacement, re-assembly and testing. Previous research has shown that the cost of cleaning is only second to the cost of parts replacement. The objective of this study is to illustrate the significance of the cleaning operation in automotive remanufacturing and to identify the factors influencing the cost of the cleaning process. Case studies on four UK remanufacturers, three automotive and one copier, were carried out. Seven key factors causing high cleaning costs were identified and categorised under two dimensions. These are the technical nature of the products and processes of cleaning and the business nature of the remanufacturer.

Keywords:

Automotive Industry; Cleaning; Remanufacturing

1 INTRODUCTION

Open loop supply chains were common in the early days of the manufacturing industry and even today it is the same for some industries and products. The continued extraction of natural resources and increasing adverse effects on the environment is pushing the society towards more sustainable way of manufacturing. In the context of sustainable manufacturing more attention is being paid to closing the manufacturing loop by developing methods to reuse products. One such method is remanufacturing while others are repair, recondition, repurpose and recycle. Product remanufacturing is a widely accepted sustainable product reuse strategy [1] in most industries due to its unique advantage of retaining a greater portion of added value during the initial manufacturing stages[2][3] and has developed to a faster growing business than some traditional industries [4].

Remanufacturing is quite an old concept for high value products and the term 'remanufacturing' has been used in literature with various meanings sometimes creating an ambiguity. In 1983 Lund[5] in his book on the experiences of United States' remanufacturing industry comprehensively defines remanufacturing "as an industrial process in which worn-out products are restored to like-new condition through a series of industrial processes in a factory environment, a discarded product is completely disassembled, useable parts are cleaned, refurbished, and put into inventory. Then the new product is reassembled from the old and, where necessary, new parts to produce a fully equivalent and sometimes superior in performance and expected lifetime to the original new product". Since then many research has been conducted on this subject in variety of industries contributing some improvements and simplifications to the definition and concepts of remanufacturing. For the purpose of this paper the definition published by the British Standards Institute is used. BS 8887-220:2010 - Design for manufacture, assembly, disassembly and end-of-life processing (MADE) and BS 8887-2 Design for manufacture, assembly, disassembly and end-of-life processing (MADE) Part 2: Terms and definitions, defines remanufacturing as 'returning a used product to at least its original performance with a warranty that is equivalent to or better than that of the newly manufactured product'[6][7].

The remanufacturing process consists of several important steps (Please refer to Figure 1). Firstly the used product, which is known as the 'Core', is received at the remanufacturing facility. Then the product is fully disassembled in to part level and then each part is cleaned. For example in automotive gearbox remanufacturing, the parts would be gear box housing, all internal gears, shafts, bearings, connecting bolts and nuts, couplings and shifter mechanisms. The main purpose of cleaning is to facilitate inspection and damage correction, and thus make the parts to like new in condition. The process of cleaning requires one or multiple processes including both manual and machine operations. The correct extent of cleaning is cleaning the product up to like- new condition. However, it is difficult to measure the level of cleaning irrespectively as there is no standard yardstick available. In practice it is mostly done by visual inspection and then determining which is good enough by experience of the workers. This also causes a difference in cleaning efforts and hence costs for each remanufacturer.

The cleaned parts are then inspected for their quality and performance. Parts which fail the expected standard are either scrapped or sent for component remanufacture. Scrapped parts are replaced with new or remanufactured parts. Some critical parts which have limited operational life such as bearings are replaced with new parts irrespective of

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their condition to ensure the required quality and hence the required guarantee. Rebuilding of the product is then carried out by assembling the parts together according the original equipment manufacturers (OEM) specification. As the last step of remanufacturing the assembled product is subjected to an operational performance test which is similar to that used to test a new product during initial manufacture. In the event of using remanufactured components, the component should also be tested individually according to OEM standards before assembly to ensure successful component remanufacture.

Almost all the remanufacturing steps discussed above are highly labour intensive and time consuming unlike the operations in initial manufacturing which may use automation. This can make remanufacturing a costly operation so that sometimes it is not worth opting for remanufacture instead of the other end-of-life processes. Compared to the other steps of remanufacturing cleaning accounts for a considerable portion of the cost of automotive remanufacturing [8]. It is of paramount importance that the costs of product recovery activities are limited to make them economically viable and hence sustainable. Therefore this research aims at investigating factors for higher costs in the cleaning process of automotive remanufacturing and suggests ways in which these costs could be reduced.

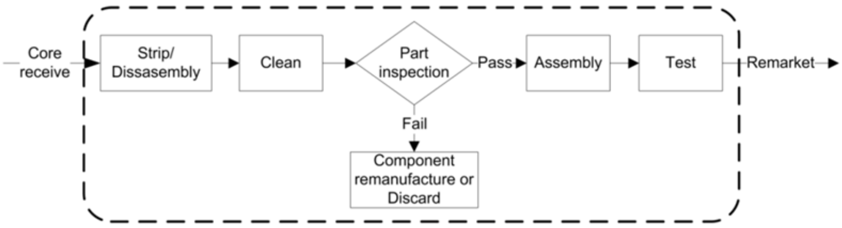


Figure 1: General process of Remanufacturing

2 LITERATURE REVIEW

Literature is enriched with a range of research on various aspects of remanufacturing in a variety of industries. It is stated that remanufactured products consumes about 50% to 80%less energy to produce when compared with a new product manufacture but with the comparable quality level [9]. Further there could be production cost savings from 20% to 80% compared with conventional manufacturing making remanufacturing a financially sound operation [2][9]. A study on environmental savings through remanufacturing of compressors has shown that the amount of greenhouse gas emission of remanufactured product is around 90% less than the manufacturing new compressor and it is 50% cheaper [10].

When it comes to automobile industry, it is estimated that 8-9 million vehicles are discarded every year in the European Union of which a major proportion is recycled meaning that an average value of 75% by weight of a vehicle is being recycled [11]. The above volume is comprised of the components that are discarded during remanufacture and components that are not considered for remanufacture. The large quantities discarded and high residual values of automobiles encourage reuse strategies to be followed. Hence it is important to develop cost effective strategies in remanufacturing. It has been found that the cost of cleaning seconds only to new parts replacement within reassembly operation in a survey undertaken in US automotive remanufacturing sector [8].

A study on the Swedish remanufacturing industry focusing on automotive and household appliances [12] has indicated that cleaning and damage correction steps are the most critical steps in the remanufacturing process. The cost for cleaning is largely from labour cost component among other capital and overhead costs. This is because there are few automated or machine assisted processes for cleaning. Other costs arise from consumables like chemical detergents and other factory overheads like electricity to operate cleaning machinery. So the time spent on cleaning is vital in controlling the cleaning costs involved. An assessment on US remanufacturing practices [13] indicates that cleaning accounts for the major portion of total remanufacturing processing time with an average of 20% spent on cleaning operation. One more reason for these excessive cleaning time is the requirement of multiple processing within the cleaning operation [4]. A study on energy intensities in diesel engine component manufacture in US[14] states cleaning remains a dominant energy consumer for remanufacturing of all of the engine components.

3 METHODOLOGY

A comprehensive literature survey on product remanufacturing was undertaken to figure out the issues of remanufacturing. The nature of the research objectives demands multiple case study approach as discussed in [15]. Four remanufacturing companies in the United Kingdom were chosen out of which three were in the automotive remanufacturing industry and the other in office equipment, (the photo copier) remanufacturing industry. Senior technical managers and operational level staff were interviewed onsite. Direct observations and company documents were used to understand the remanufacturing process in general and the importance and procedures of cleaning in particular.

4 CASE STUDIES

The entire process of remanufacturing from gate-to-gate was studied during case study visits. A comparison of case companies with regard to industry sector, category of remanufacturing, volume of operation and nature of cleaning operation is presented in Table *1*. Automotive transmission and engine components (such as gear wheels, shafts, couplings, valve bodies, torque converters, pistons, cylinder blocks, etc) require different degrees of cleaning and often done by different machine aids. Machine aided cleaning used in the case companies were, spray cleaning, baking, chemical bath agitating, shot blasting, and vibration grits cleaning. Manual washing, which is the most common, may still be required even after one stage machine aided cleaning.

Table 1 : Comparison of case companies

	COMPANY A	COMPANY B	COMPANY C	COMPANY D
Sector	*Automotive*	*Automotive*	*Automotive*	*Copier*
Nature of business	*Both automatic and manual transmission remanufacturing*	*Manual transmission and engine remanufacturing*	*diesel engines and transmissions, cylinder heads*	*Photo copier remanufacturing and after sales services*
Category	*Independent remanufacturer*	*Contract remanufacture*	*OEM*	*Independent catering for limited brands*
Company size (employees)	*25 approx.* *SME*	*75 approx.* *SME*	*300 approx.*	*15 approx.* *SME*
Average production (approx.)	*600 units/year*	*15,000 units/year*	*Complex*	*400 units/year*
Nature of cleaning operation	*Machine and manual* *Uses aqueous based detergents and degreasers*	*Varity of machines and manual* *Uses aqueous based detergents and degreasers*	*Varity of machines (Ex. vibration) and manual cleaning*	*Only Manual cleaning* *Uses aqueous based detergents*

Company A, uses a spray cleaner machine and manual cleaning of automobile transmissions parts. After cleaning they spray paints the gearbox cases in bringing those to like new condition. Whereas company B uses only cleaning techniques in bringing the gearbox casings to like-new condition. These include the spray machine wash and then shot blasting to get the natural aluminium outlook without painting it. For other inside components they use dipped cleaning with kerosene and aqueous detergents, vibration grits cleaning and manual cleaning. Company B spends 40% of its total remanufacturing time for cleaning operation during manual transmission cleaning. This has been largely contributed by the manual cleaning operation. Company C also uses manual cleaning and variety of machine cleaning techniques. It was mentioned that consumables of cleaning alone accounts for 10% from the total cost of remanufacturing in company C.

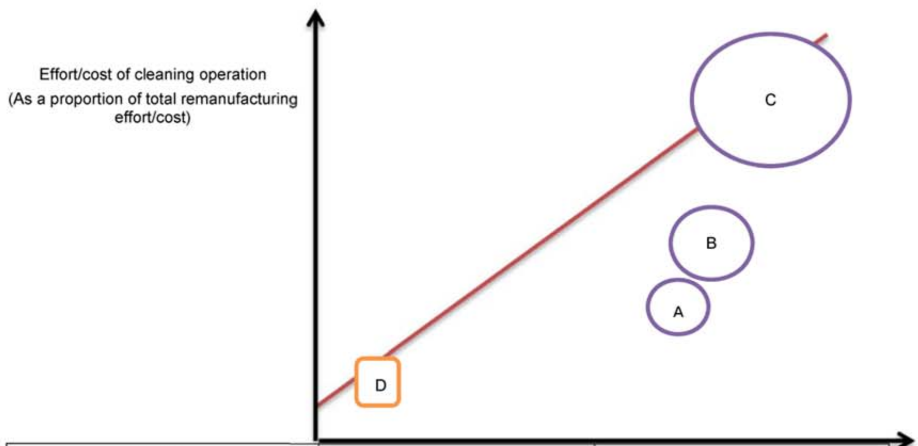
A study on automotive parts remanufacturing [8] reveals five main reasons for cleaning difficulties; namely the size of parts/orifices, environmental regulations, excess debris, material type and corrosion. These were enquired and confirmed by the case studies A, B and C. Additionally two new important factors were also found. These are the output form of the remanufactured product and the approaches to cleaning by individual remanufacturer. The attention to cleaning is higher in component remanufacture than whole unit remanufacture. For example during whole engine remanufacture versus piston remanufacture, there is much higher effort is needed for the later. This is because the customer is comparing the remanufactured component (piston) with its new counterpart. However during whole engine remanufacturing the attention/effort needed to clean the same piston would be much lesser. Some remanufacturers use finishing operations, like painting, to bring products to like new condition thus reducing the efforts of cleaning. These kinds of alternative approaches to cleaning by some remanufacturers may reduce the costs incurred for cleaning.

Attention for cleaning was comparatively low in company A, medium in Company B and high in company C. This may be due to the fact that OEMs and contract remanufacturers are much more concern about the brand value of products. Further they have to incur higher costs when complying with environmental regulations than for small scale independent remanufacturers who outsource the waste disposal. The use of technology also increases from company A to C as company wealth, volume and complexity of operation increases. Furthermore company C has to put an extra effort for cleaning as their output form of products includes remanufactured spare parts other than whole units. In contrast, company D, which is in the copier industry has a relatively lower extent of cleaning which requires only manual cleaning with aqueous detergents as it does not contain large amounts of debris and they use a final painting operation. Further copiers have fewer parts, less intricate components and simpler joining methods compared to automotive parts.

5 FINDINGS

Seven factors were identified which make cleaning costlier (please refer left most column in Figure 2). Out of which first five was mentioned in literature and also confirmed through the case studies. New two factors, output form and approaches to cleaning, were revealed through case studies. These seven factors can be categorised to two main dimensions. The first is the technical difficulty due to physical characteristics of the product and/or process which makes cleaning process more complex. This demands extended labour and machine hours adding up to the cost of cleaning. The first four factors in the list (Figure 2) belong to this category. The second dimension is the factors arising from the nature of the business of the remanufacturer. Characteristics like company scale, volume and variety of operation, output form and internal standards coupled with the brand image are concerned under business nature. The last three factors in the list could be categorised under second dimension. The costs associated with cleaning consumables, overheads and compliance to cleaning waste disposal regulations may increase due to the factors under second dimension.

Figure 2 shows the relative costs incurred for cleaning in each of the case studies. The circles represent automotive remanufacturers and square represents the copier remanufacturer. The relative size of object shows the size of the organisation in terms of employees and volume of operation. The figure is not to scale but represents a fair enough picture based on the information gained during the case studies. The x - axis represents the factors which make cleaning costlier and the y - axis represents the cost of cleaning as a proportion of total remanufacturing cost in each company.



FACTOR		
Part complexity (shape, size)	*Low*	*High*
Excessive debris	*Low*	*High*
Material type	*Easy (ex. Ferrous)*	*Difficult (ex. Aluminum)*
Corrosion	*Low*	*High*
Environmental regulations	*Low applicability*	*High applicability*
Output form	*Whole units (ex. Complete transmission or engine)*	*Part level (ex. Crank shaft, piston)*
Approaches to cleaning (due to brand consciousness and internal standards)	*Simple*	*Complex*

Figure 2 : Cost of cleaning vs factors affecting cleaning

It could be concluded that both dimensions equally contribute to the cost of cleaning. It is important to identify what are the factors that mostly affect in a given context and address them to bring down the cost of cleaning during remanufacture. Individual companies need to set their own targets in cleaning operations and invest accordingly in gaining a cost advantage.

6 SUMMARY

The factors making higher cleaning efforts have been identified. Those factors affect every remanufacturer depending on the nature of their operation and type of the products. The findings of previous research have been confirmed and some new factors were also identified. The research emphasises the significance of the cleaning operation as a high cost contributor for remanufacturing. Higher cost of remanufactured products may hinder their competitiveness in the market place which affects sustainable manufacturing. The authors believe that this knowledge would encourage product designers to consider more about the aspect of cleaning during the product design stage (Design for Cleaning) thus assisting them to design more sustainable and environmentally friendly products.

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8 REFERENCES

[1] P. Zwolinski and D. Brissaud, "Remanufacturing strategies to support product design and redesign," *Journal of Engineering Design*, vol. 19, no. 4, pp. 321–335, 2008.

[2] R. Giutini and K. Gaudette, "Remanufacturing: The next great opportunity for boosting US productivity," *Business Horizons*, vol. 46, no. 6, pp. 41–48, Nov. 2003.

[3] E. Sundin and H. M. Lee, "In what way is remanufacturing good for the environment?," in *Design for Innovative Value Towards a Sustainable Society*, M. Matsumoto, Y. Umeda, K. Masui, and S. Fukushige, Eds. Dordrecht: Springer Netherlands, 2012, pp. 552–557.

[4] V. D. R. Guide Jr, "Production planning and control for remanufacturing: industry practice and research needs," *Journal of Operations Management*, vol. 18, no. 4, pp. 467–483, 2000.

[5] R. T. Lund, *Remanufacturing, United States experience and implications for developing nations*. Center for Policy Alternatives, Massachusetts Institute of Technology, 1983.

[6] B. Walsh, "A new British Standard defines remanufacturing," *Centre for Remanufacturing and Reuse (CRR)*, 14-Nov-2008. [Online]. Available: http://www.remanufacturing.org.uk/. [Accessed: 20-Mar-2013].

[7] W. L. Ijomah, "A Model-based Definition of the Generic Remanufacturing Business Process," PhD Thesis, University of Plymouth, Plymouth, United Kingdom, 2002.

[8] R. Hammond, T. Amezquita, and B. Bras, "Issues in the automotive parts remanufacturing industry: a discussion of results from surveys performed among remanufacturers," *Engineering Design and Automation*, vol. 4, pp. 27–46, 1998.

[9] E. Sundin, M. Lindahl, and W. Ijomah, "Product design for product/service systems: Design experiences from Swedish industry," *Journal of Manufacturing Technology Management*, vol. 20, no. 5, pp. 723–753, May 2009.

[10] W. Biswas and M. Rosano, "A life cycle greenhouse gas assessment of remanufactured refrigeration and air conditioning compressors," *International Journal of Sustainable Manufacturing*, vol. 2, no. 2, pp. 222–236, 2011.

[11] S. Kumar and V. Putnam, "Cradle to cradle: Reverse logistics strategies and opportunities across three industry sectors," *International Journal of Production Economics*, vol. 115, no. 2, pp. 305–315, Oct. 2008.

[12] E. Sundin and B. Bras, "Making functional sales environmentally and economically beneficial through product remanufacturing," *Journal of Cleaner Production*, vol. 13, no. 9, pp. 913–925, Jul. 2005.

[13] N. Nasr, C. Hughson, E. Varel, and R. Bauer, "State-of-the-art assessment of remanufacturing technology." Rochester Institute of Technology, 1998.

[14] J. W. Sutherland, D. P. Adler, K. R. Haapala, and V. Kumar, "A comparison of manufacturing and remanufacturing energy intensities with application to diesel engine production," *CIRP Annals - Manufacturing Technology*, vol. 57, no. 1, pp. 5–8, 2008.

[15] R. K. Yin, *Case Study Research*. London,UK: Sage, 2003.

APPENDIX III: Process flow diagram of company D